Emerging Concepts for Synthesis of Thermally Engineered Materials and Structures

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14. ABSTRACT
Heat Exchanger Concepts -Stocastic Cellular Metal Microheat Exchangers -Periodic Cellular Metal Heat Exchangers Thermal Protection Coatings -Pore Morphology Control -Manufacturing Concepts for Low K Multi-component Oxides

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Emerging Concepts for Synthesis of Thermally Engineered Materials and Structures

OUTLINE

Heat Exchanger Concepts

-Stocastic Cellular Metal Microheat Exchangers

-Periodic Cellular Metal Heat Exchangers

Thermal Protection Coatings

-Pore Morphology Control

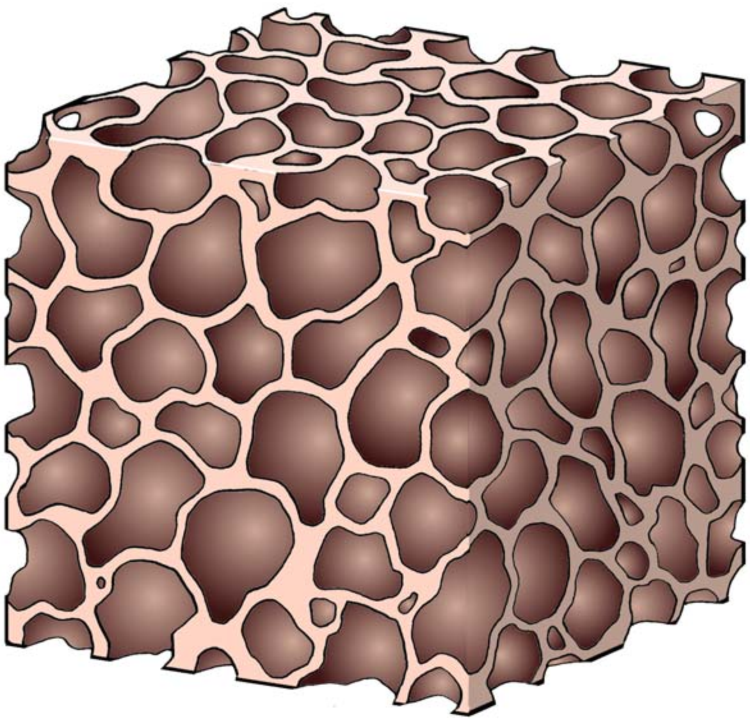
-Manufacturing Concepts for Low K Multi-component Oxides

HEAT EXCHANGER CONCEPTS

Stocastic Cellular Metal MicroHeat Exchangers

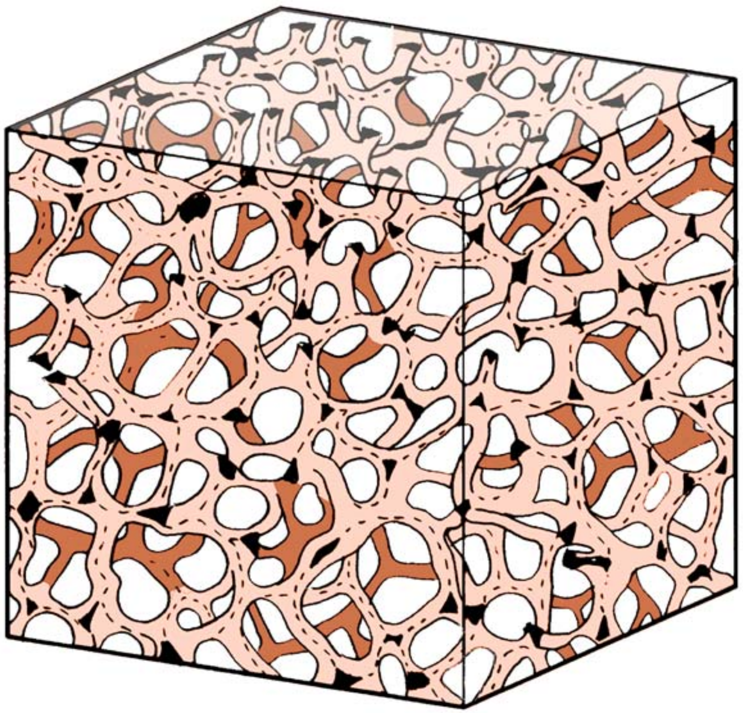
Stochastic Cellular Metals

Closed Cell Foam



fire retarding and low relative thermal conductivity

Open Cell Foam



ability to flow fluids through structure leads to high heat transfer

Stochastic Cellular Metal Heat Sink

Mode of Heat Transfer

Conduction through metal ligaments that are cooled by passage of a fluid through pores

Duocel® Foam

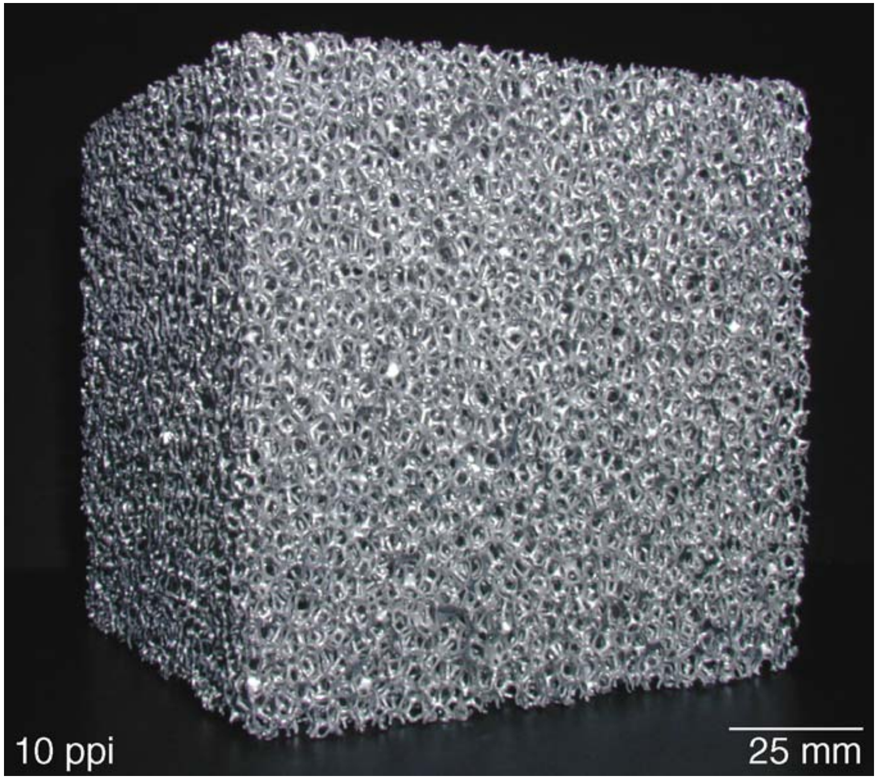
ERG Aerospace, Inc.

www.ergaerospace.com

• Materials: Al, Cu, Ni alloys

• Cell sizes: 5, 10, 20, 40 ppi

• Relative density $0.04 < p^* < 0.15$



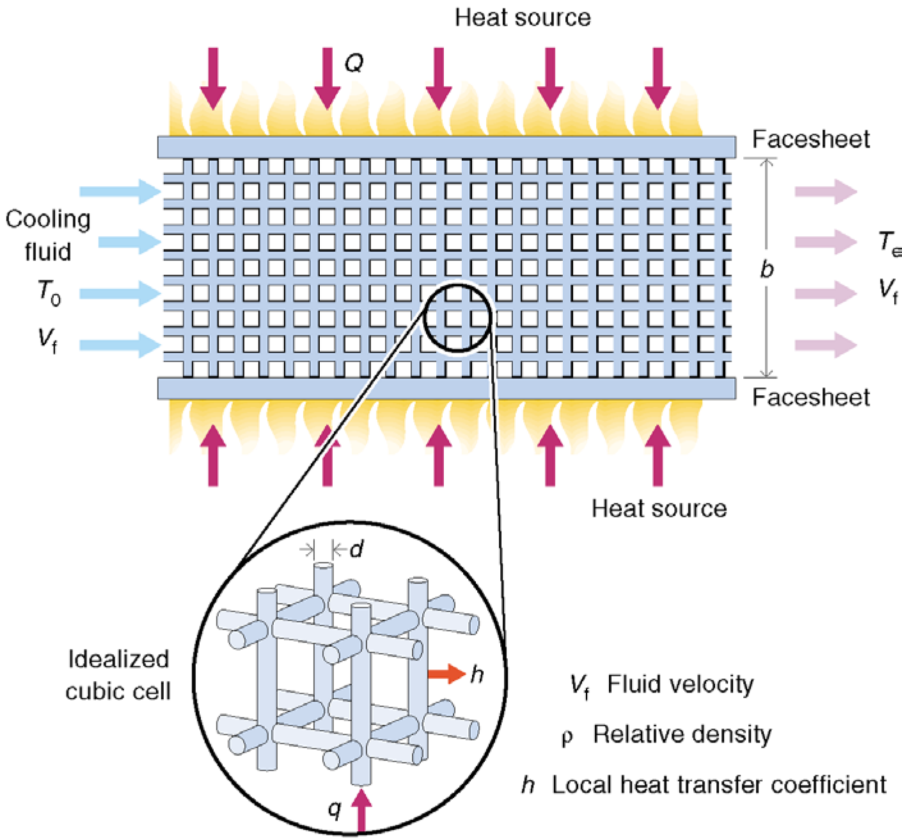
When this material is made by investment casting the ligaments are solid.

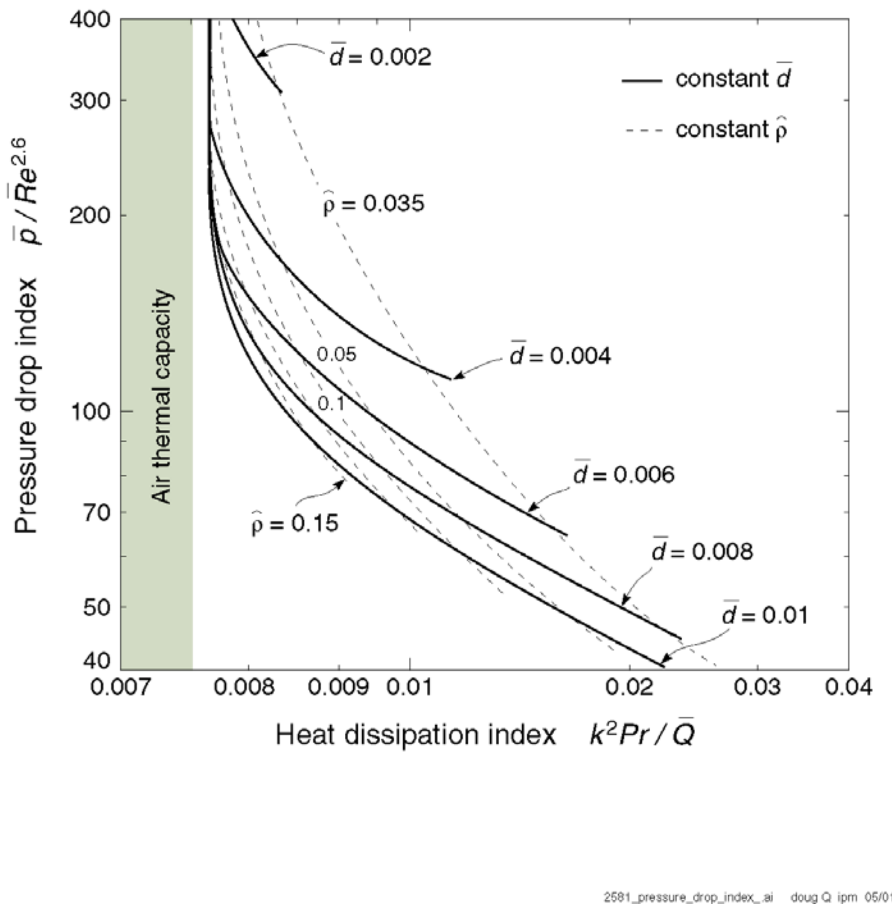
T.J. Lu, H.A. Stone, M.F. Ashby, Acta mater. 46 (10) pp. 3619-3635 (1998)

A.G. Evans, J.W. Hutchinson, M.F. Ashby, Prog. in Mater. Sci. 43 pp. 171-221 (1999)

A.G. Evans, J.W. Hutchinson, N.A. Fleck, M.F. Ashby, H.N.G. Wadley, Prog. in Mater. Sci. 46 pp. 309-327 (2000)

Thermal Management and Heat Transfer





<u>Reference:</u>

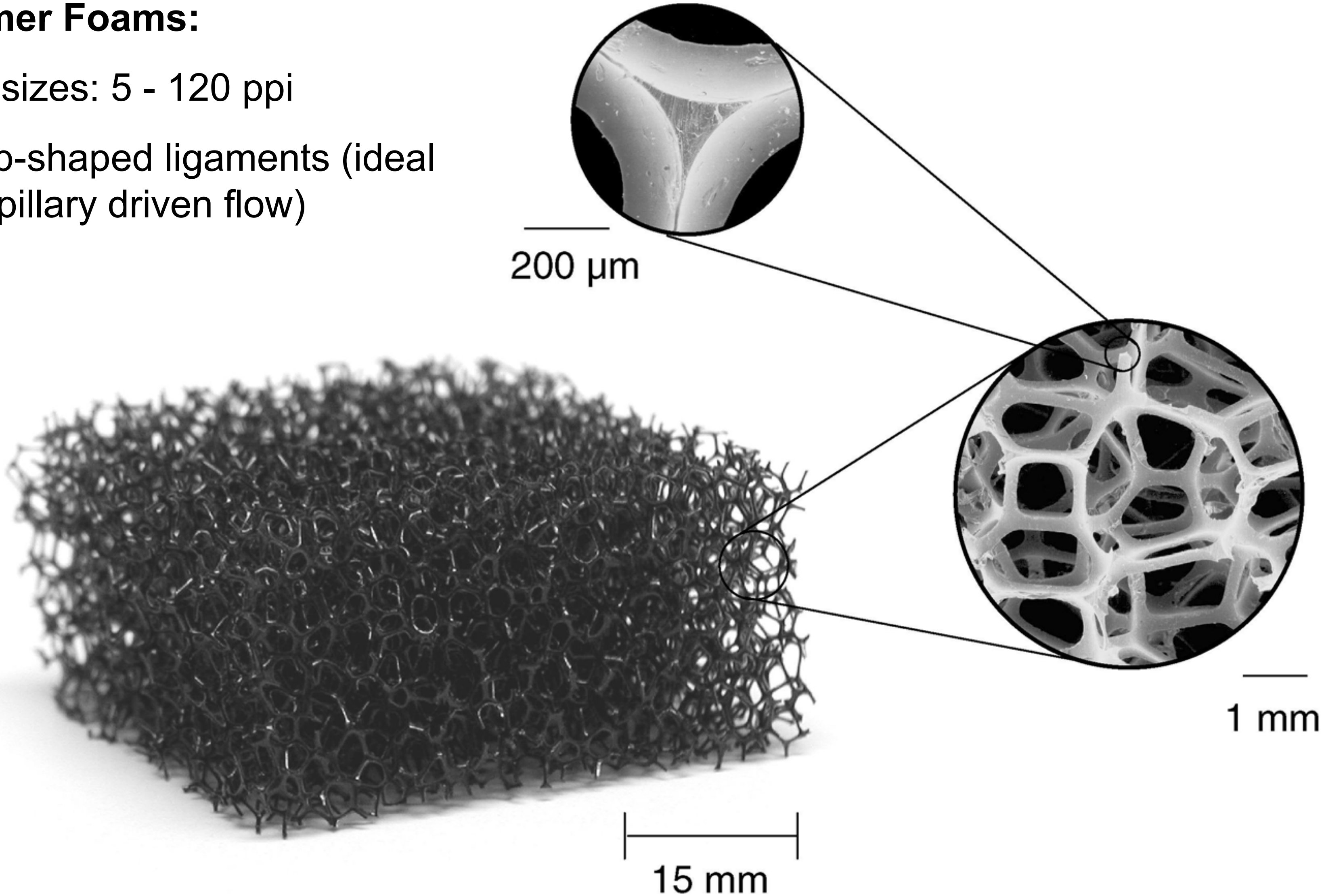
"Metal Foams – A Design Guide", M. Ashby, A. Evans, N. Fleck, L. Gibson, J. Hutchinson, H. Wadley.

Template: Open Cell, Reticulated Polyurethane Foam

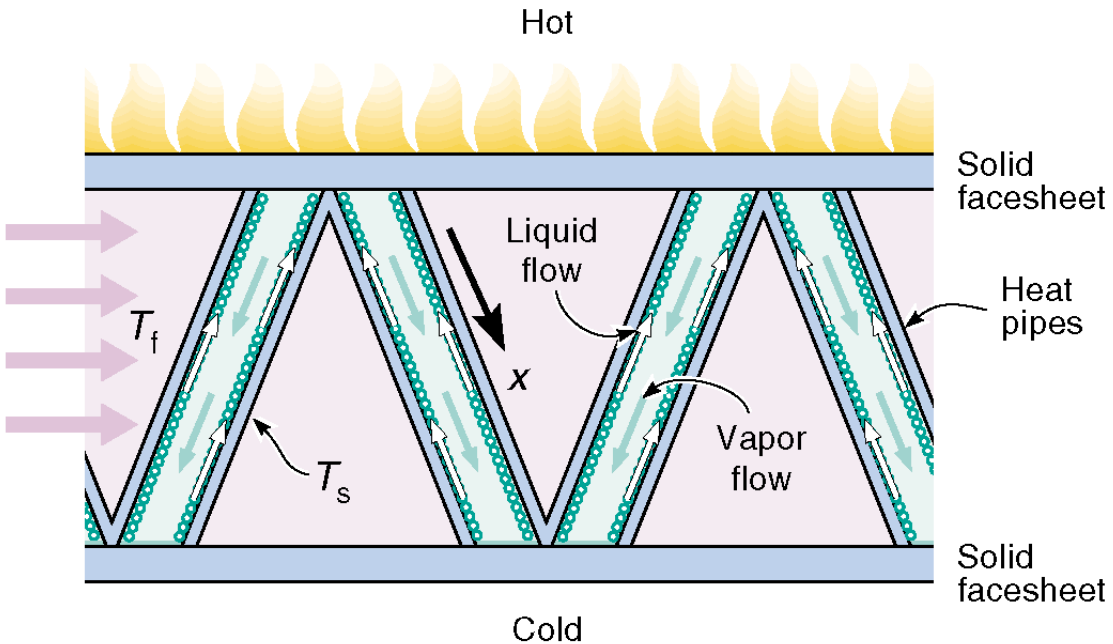
Polymer Foams:

• Cell sizes: 5 - 120 ppi

• Cusp-shaped ligaments (ideal for capillary driven flow)



Multifunctional Heat Exchanger

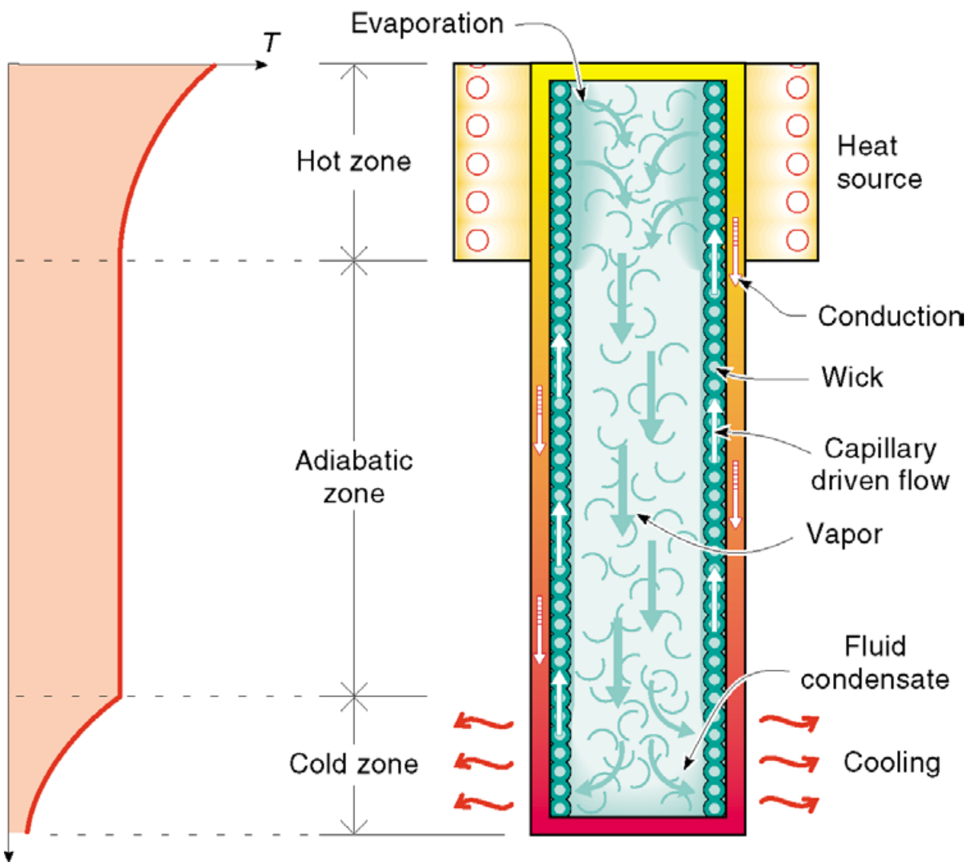


$$q = h\int_{x_1}^{x_2} \left[T_s(x) - T_f(x)\right] dx \cdot C$$

Where, *h* - heat transfer coefficient

c - projected heat pipe circuumference in the fluid flow direction

Conventional Heat Pipe



Construction:

- an evaporator or heat addition region
- an adiabatic or isothermal region
- a condenser or heat rejection region

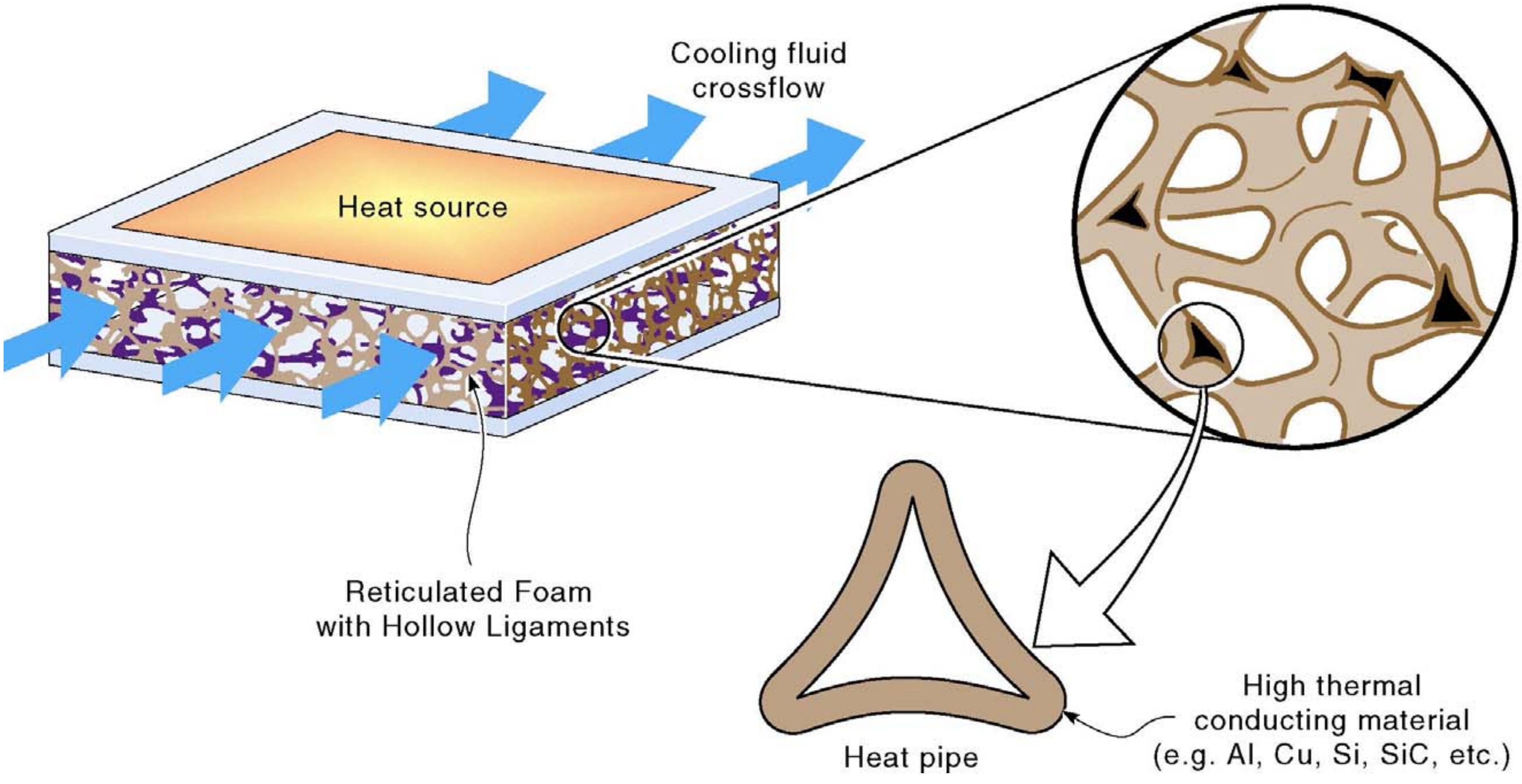
Operation:

- heat is added to the evaporator region,
- the fluid vaporizes, resulting in an increased pressure which causes the vapor to flow to the cooler condenser region
- the vapor condenses releasing its latent heat of vaporization.
- capillary forces in the wicking structure forces the liquid back to the evaporator region.

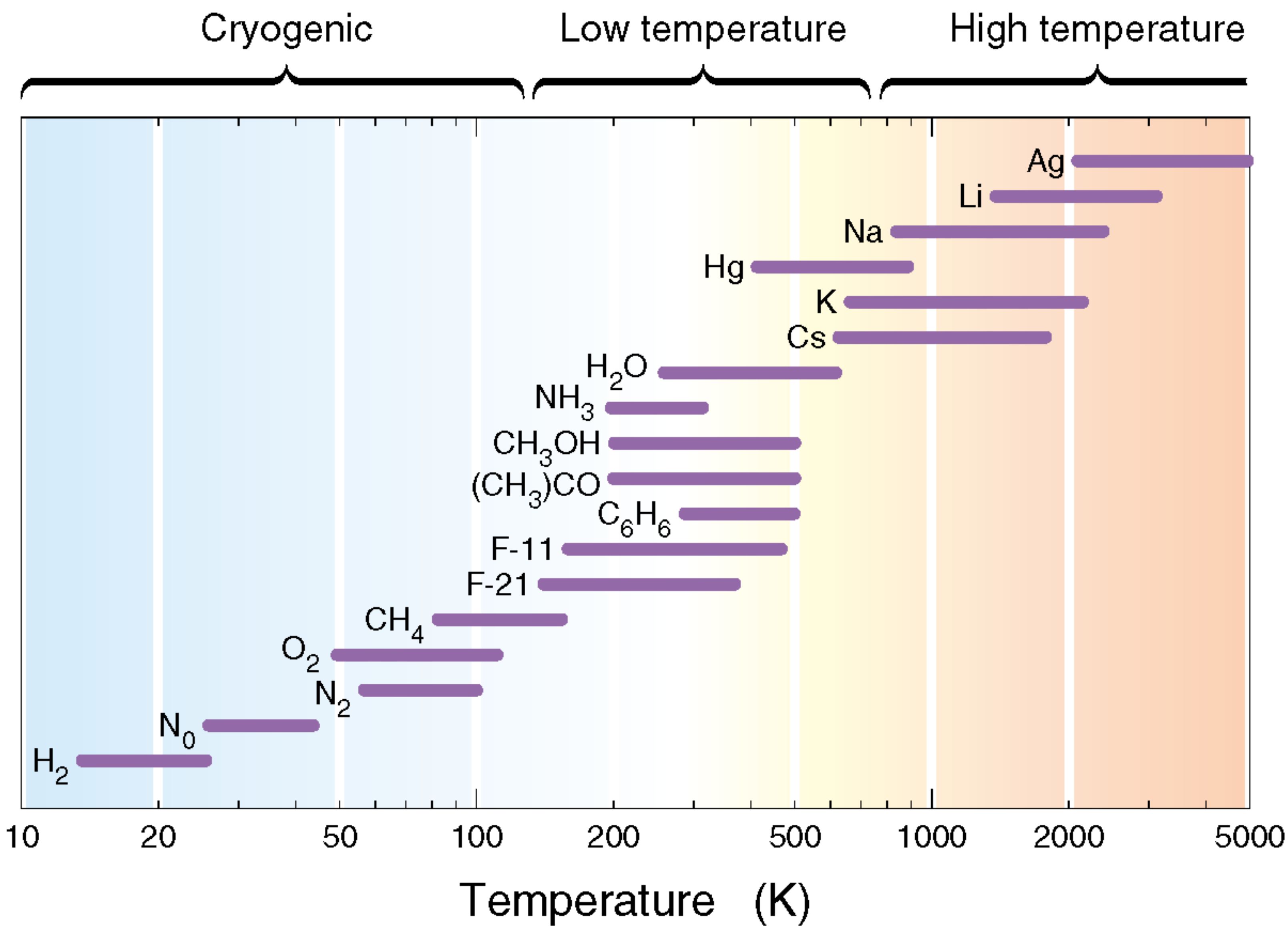
G. P. Peterson, *An Introduction to Heat Pipes*, Wiley-Interscience, N.Y. (1994)

A Foam Based Multifunctional Micro Heat-Pipe Concept

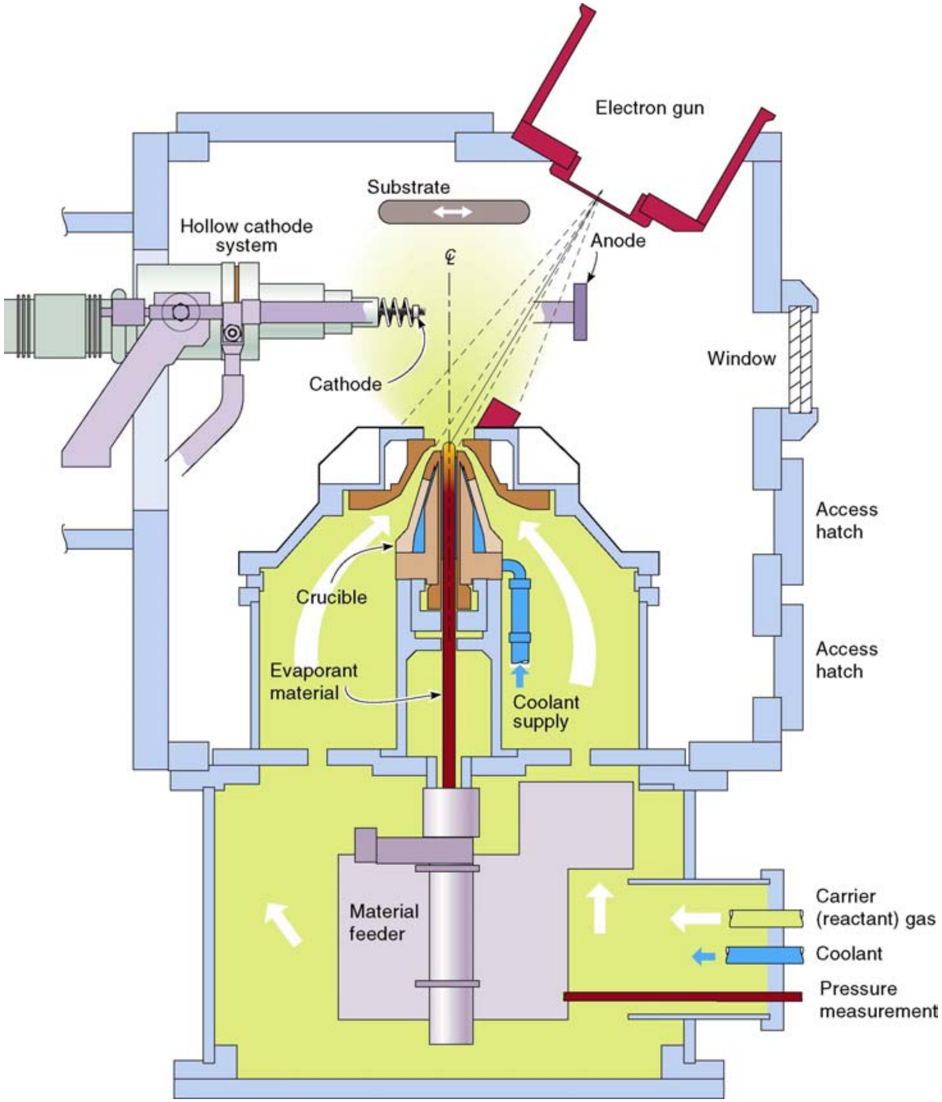
Solid Face-sheets and Stochastic Cellular Metal Sandwich Panel



Operating Range For Heat Pipe Working Fluids



Electron Beam - Directed Vapor Deposition



- **Electron beam gun**

  beam accelerating voltage = 70 kV

  maximum power = 10 kW

  high speed scanning ~ 100 kHz

  spot size < 0.5 mm

- **Multi-pump vacuum system**

  high to low vacuum (10^{-5} – 0.5 mbar)

  non-reactive carrier gas (0 – 20 slm)

  reactive carrier gas (O_2, N_2, etc.)

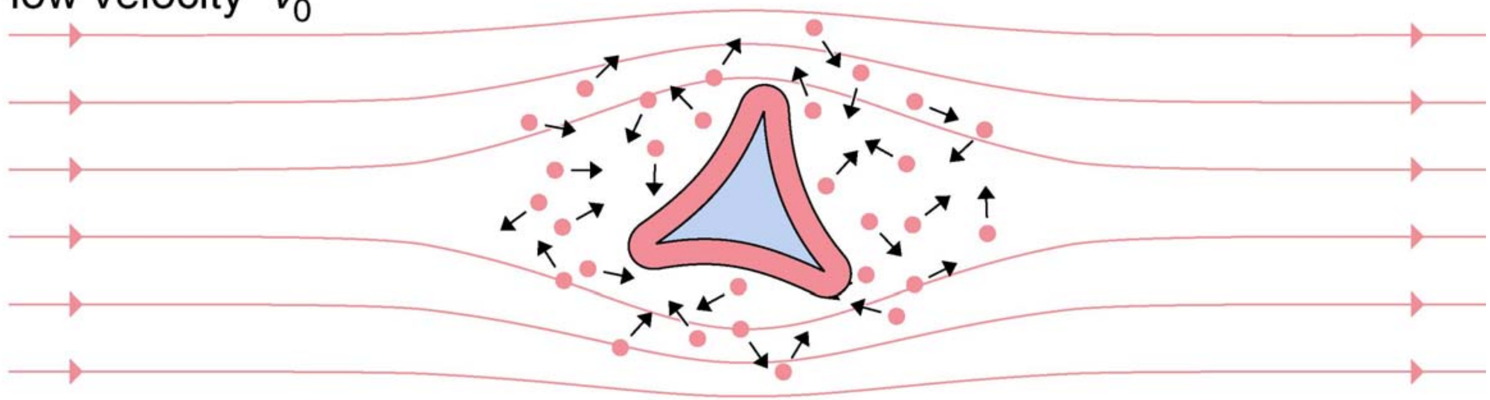
- **Hollow cathode plasma**

  high density plasma of gas and vapor stream

- **Integrated substrate biasing**

  constant or alternating, positive then negative, bias (0 – ±300 V)

Binary Scattering of Atomic Vapor in a Rarefied Gas Flow



v_0 increase reduces residence time

P_0 increase reduces mean free path

Mean collision frequency, ν

$\nu = \pi n d^2 c_r$

d = molecular diameter (m)

n = number density of background atoms(#/m^3)

c_r = relative velocity (m/s)

Mean free path, λ

$\lambda = c/\nu$

c = thermal speed (m/s)

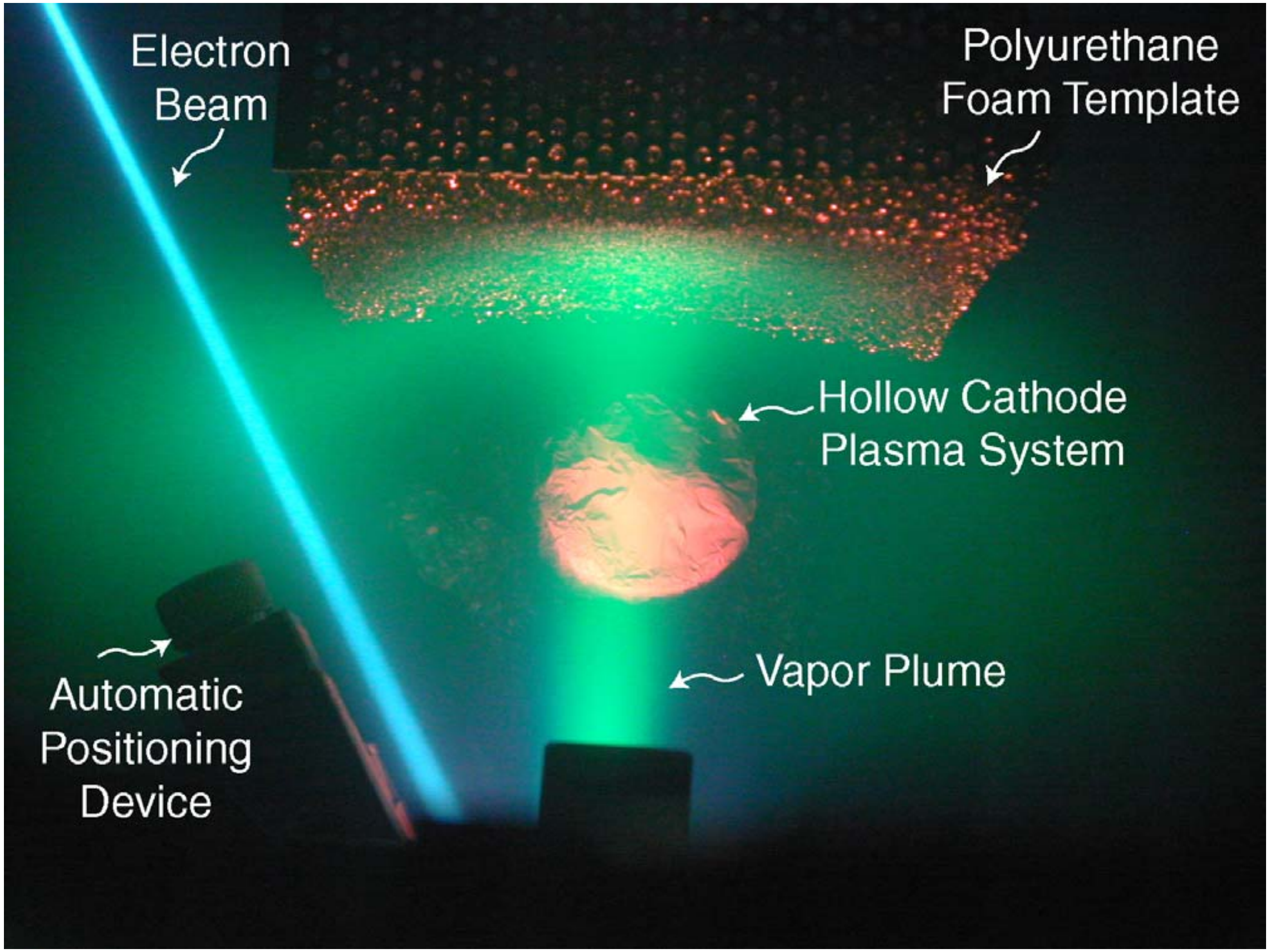
For He, $\lambda \sim 200\mu m$ @ 0.5 Torr

Collision rate, N

$N = \frac{1}{2} n\nu$

Vapor condenses by binary scattering from streamlines that carry flow around the vapor. The local coating thickness depends on the number density of the atoms (I.e. local pressure) and the flow velocity.

Coating Open Cell Reticulated Ligaments (Directed Vapor Deposition)



Metal/Alloy Deposition

Al, Cu, Ni, Stainless Steel, many other alloys

Non Line-of-Sight Coatings

Promoted by low vacuum environment

High Deposition Rates

Up to 100 μm/min

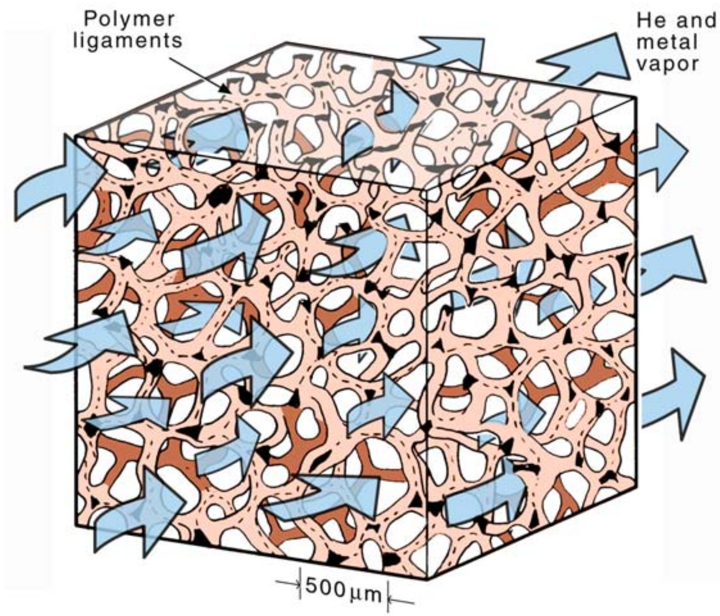
Electron Beam – Directed Vapor Deposition

Plasma-assisted DVD combines four process technology components

- high voltage electron beam evaporation
- low-vacuum, flowing-gas vapor transport
- high-density gas and vapor plasma activation
- pulsed or constant substrate biasing

EB-DVD on Open Cell Reticulated Templates

Step 1: Metal Deposition

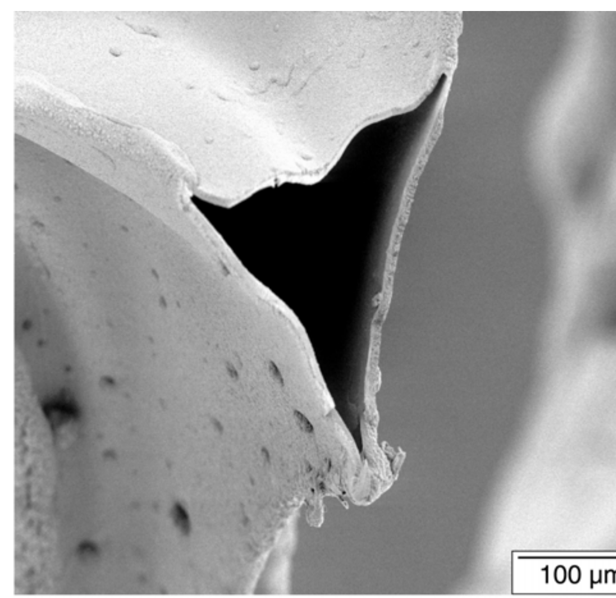


Deposition Process Variables:

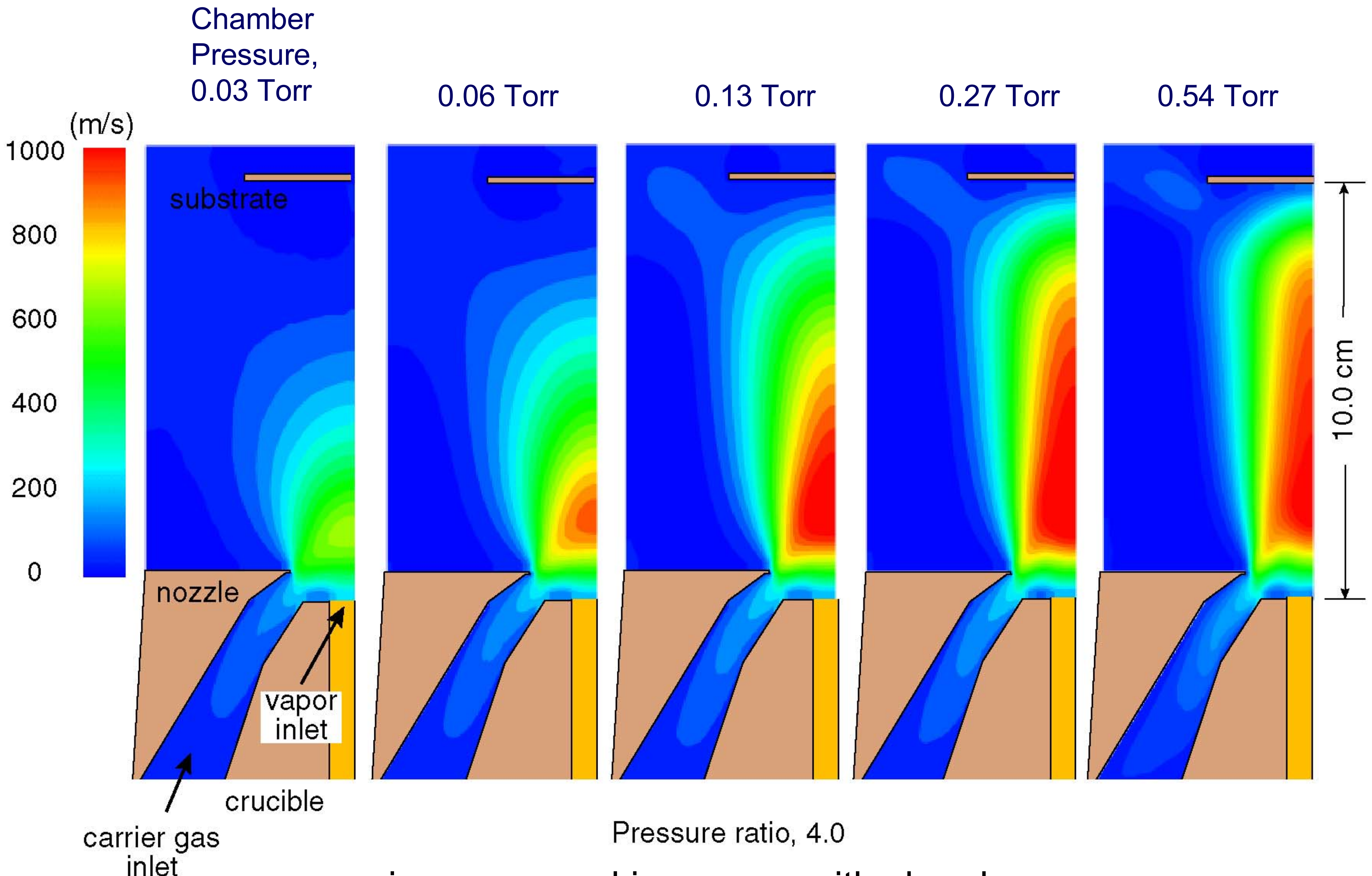
- electron beam power
- carrier gas flow
- chamber pressure
- pressure ratio, P_u/P_c

Step 2: Thermal Decomposition of Polyurethane Foam

- thermally decompose the foam in vacuum (~10^{-5} Torr) by heating at 1°C/min to 250°C, and holding for two hours
- results in complete removal of the polymer core with minimal carbon residue

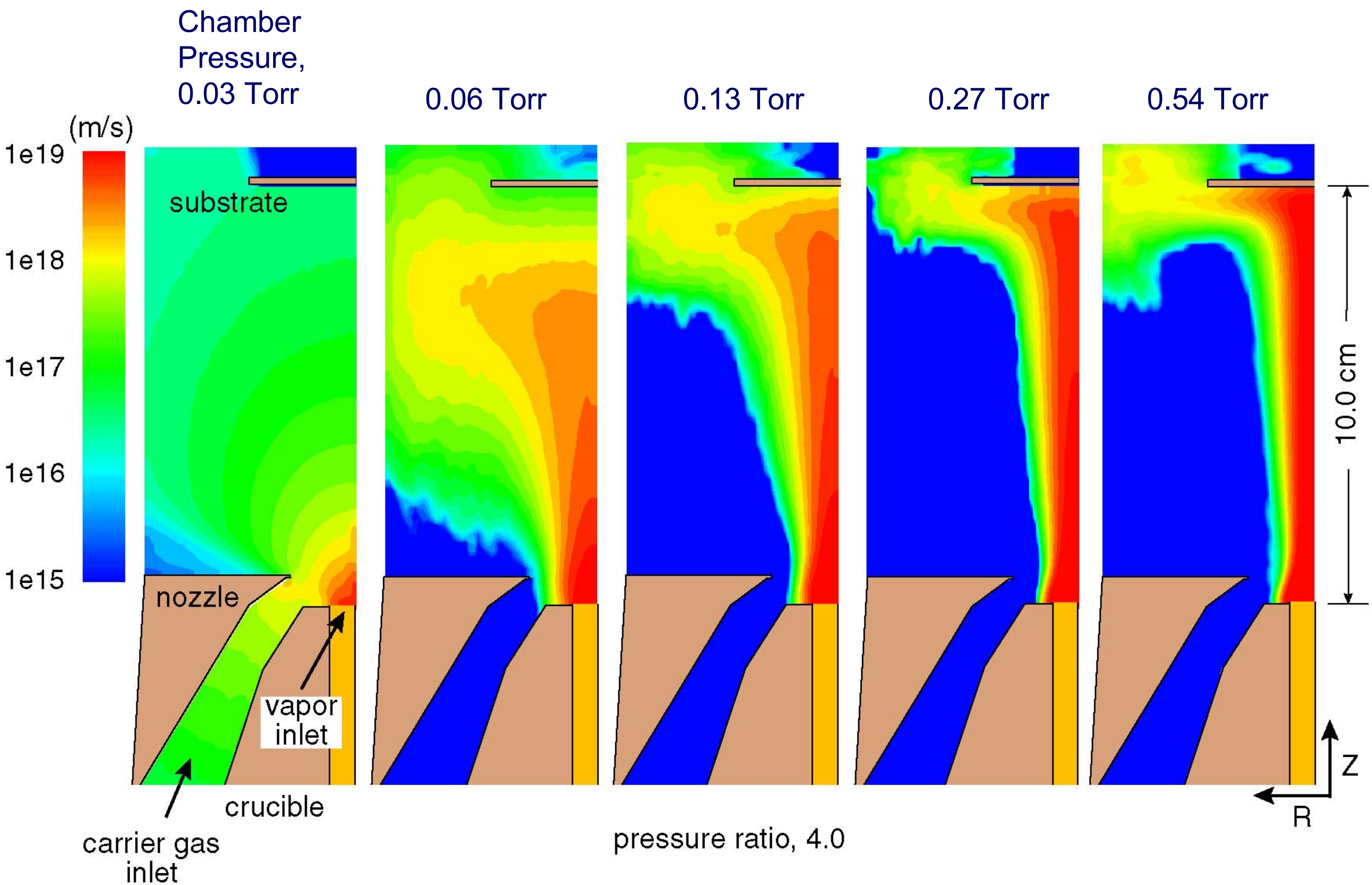


DSMC Simulations: Carrier gas (helium) speed axial direction



carrier gas speed increases with chamber pressure

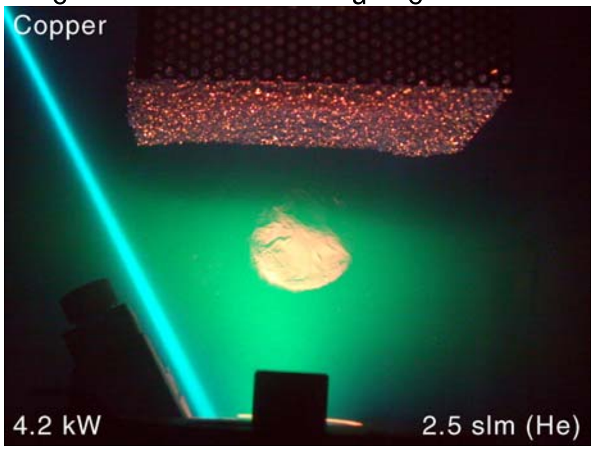
DSMC Simulations: Vapor Distribution



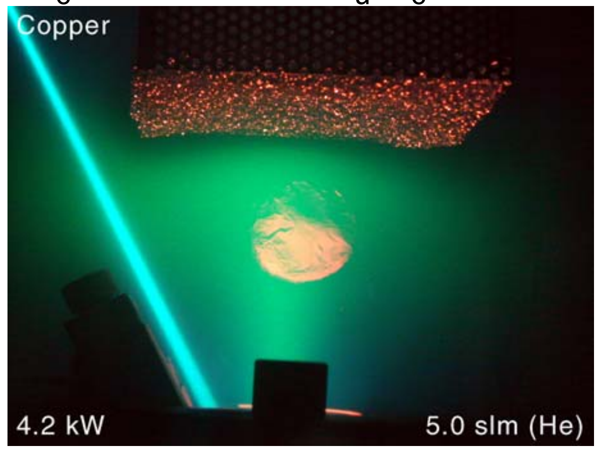
Vapor focusing increases with chamber pressure

Gas Jet Flow Effects

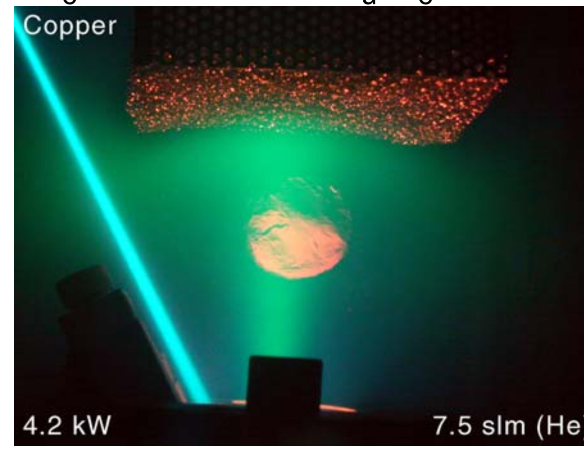
P_c = 0.042 torr, P_u/P_c = 5.71



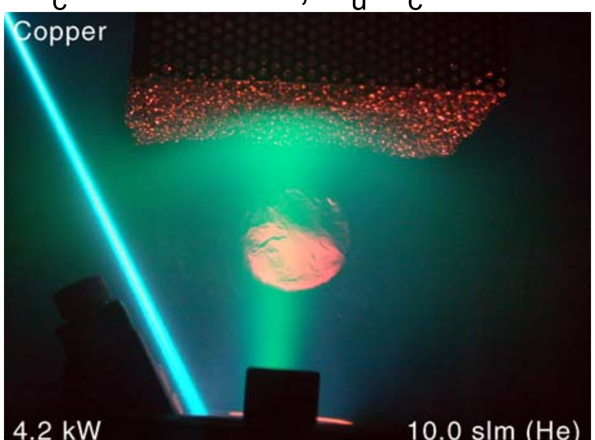
P_c = 0.075 torr, P_u/P_c = 5.00



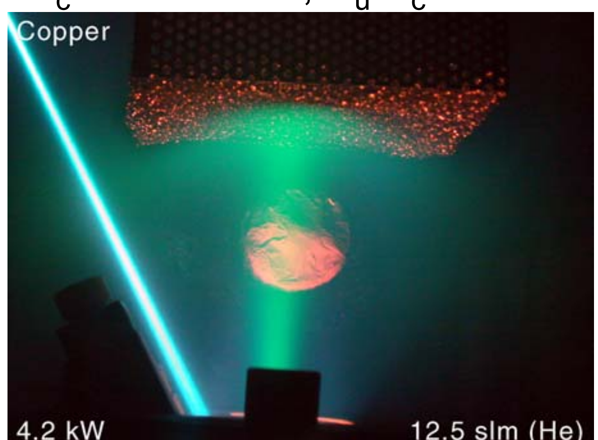
P_c = 0.105 torr, P_u/P_c = 4.79



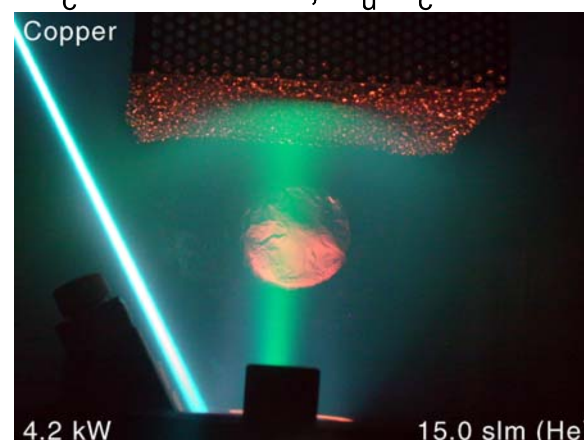
P_c = 0.135 torr, P_u/P_c = 4.67



P_c = 0.165 torr, P_u/P_c = 4.50



P_c = 0.195 torr, P_u/P_c = 4.23

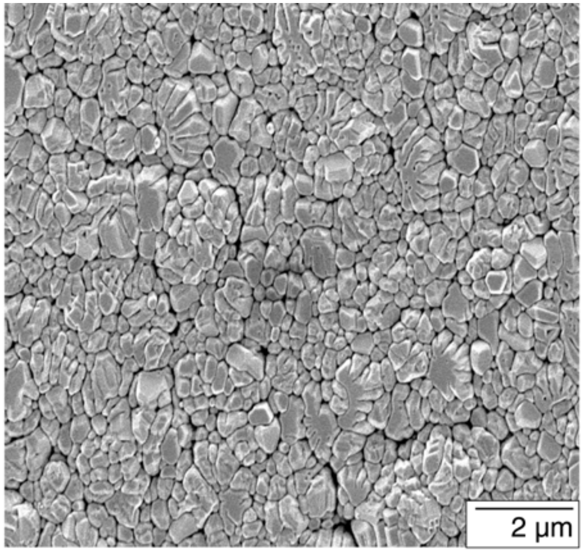


Polyurethane foam template, cell size = 20 pores per inch (ppi)

Copper Deposition: P_c = 0.1 Torr, P_u/P_c = 4.6, 7.5 slm (He)

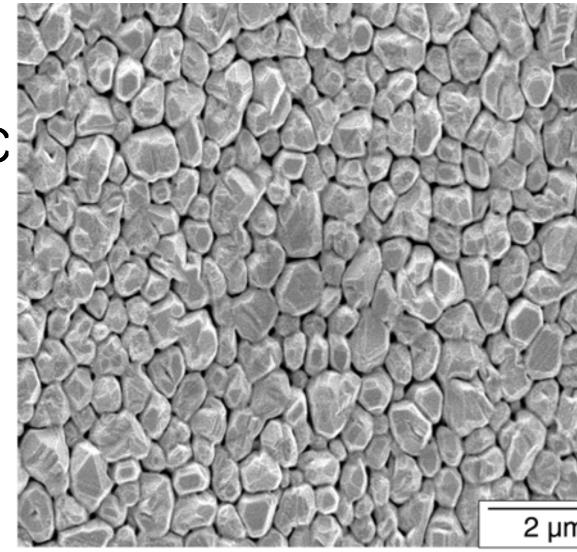
2.80 kW

T_f = 138 °C



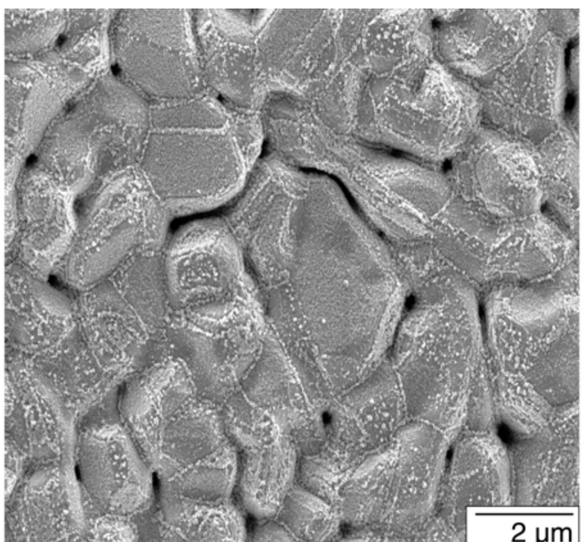
3.50 kW

T_f = 194 °C



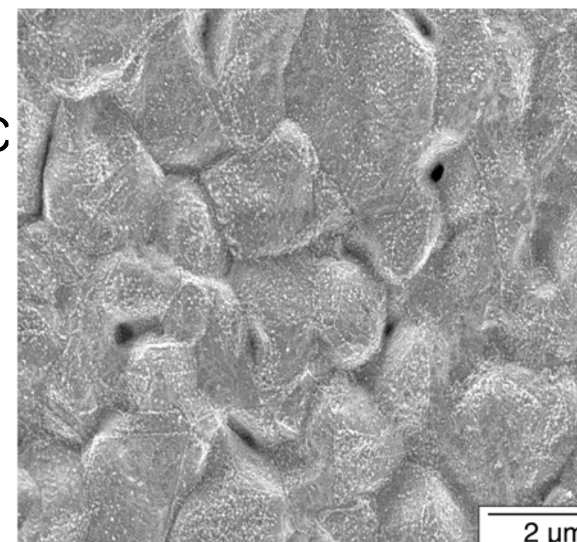
4.20 kW

T_f = 233 °C



4.90 kW

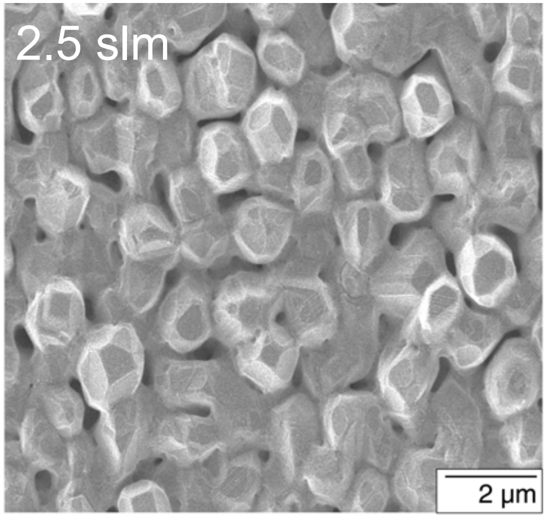
T_f = 279 °C



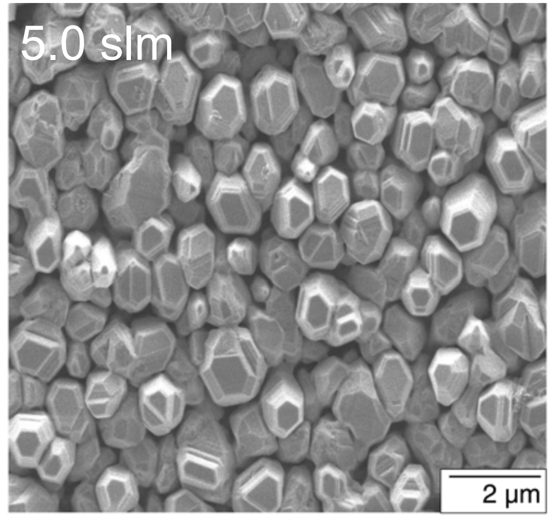
planar glass substrate, deposition time = 10 min

Copper Deposition: beam power = 4.2 kW

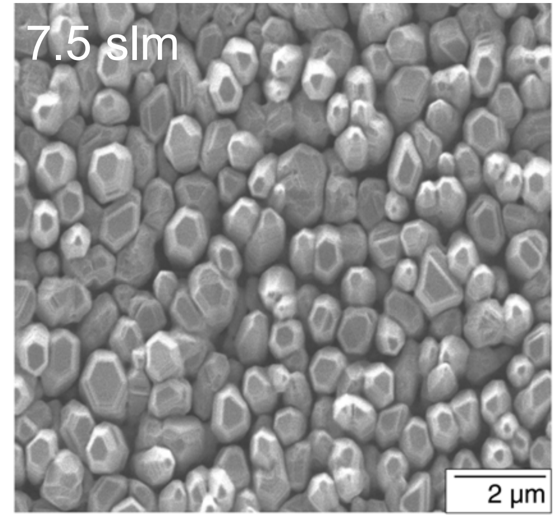
P_c = 0.042 torr, P_u/P_c = 5.71



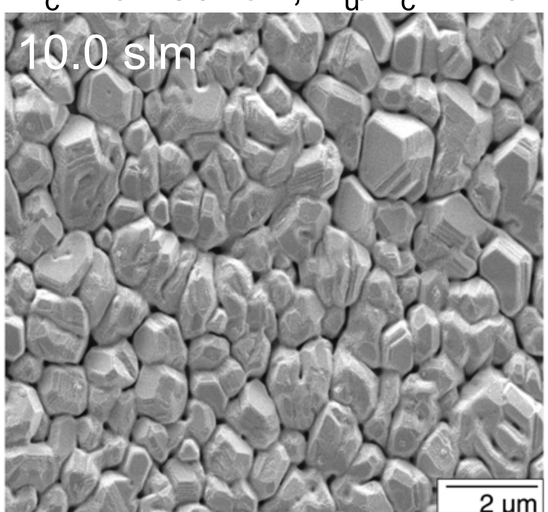
P_c = 0.075 torr, P_u/P_c = 5.00



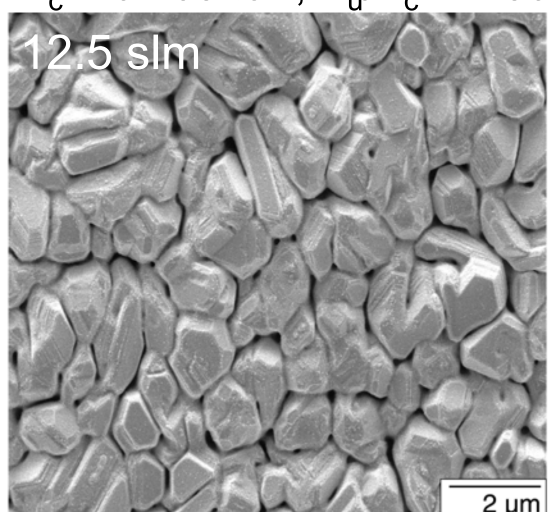
P_c = 0.105 torr, P_u/P_c = 4.79



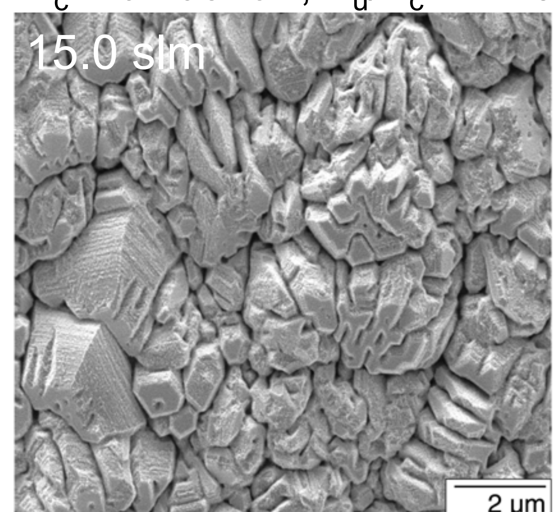
P_c = 0.135 torr, P_u/P_c = 4.67



P_c = 0.165 torr, P_u/P_c = 4.50



P_c = 0.195 torr, P_u/P_c = 4.23



planar glass substrate, deposition time = 10 min

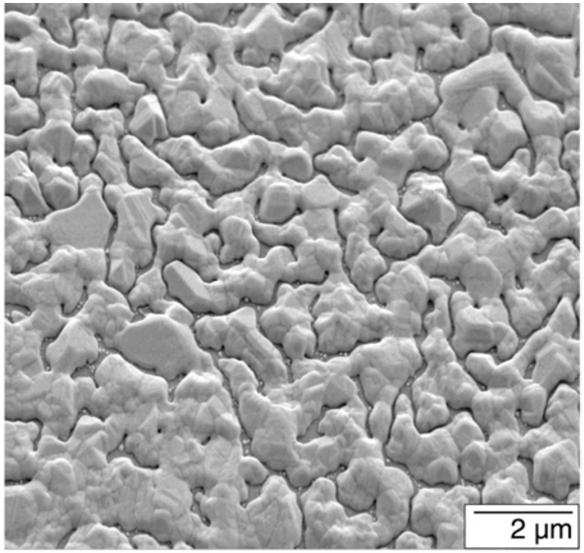
Plasma Activated EB-DVD Deposition of Copper

beam power = 4.2 kW, 7.5 slm Argon carrier gas

Backside

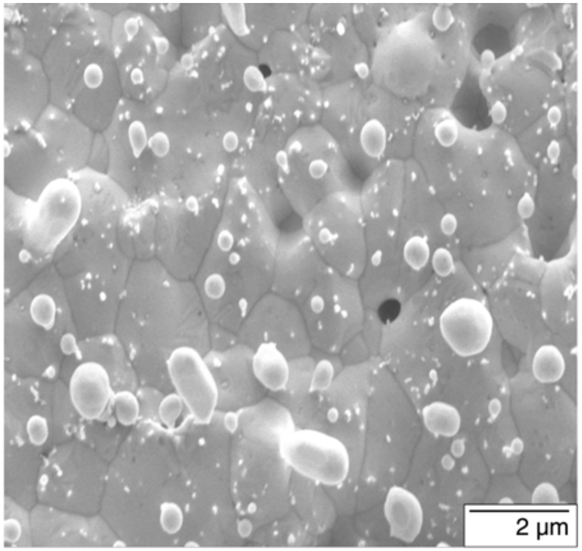
Deposition Conditions:

no plasma



Deposition Conditions:

plasma activated (DC^+ 9V preheat to ~500°C, DC^- 75V during deposition)



Synthesis of Open Cell, Reticulated Copper Foams

Deposition Conditions:

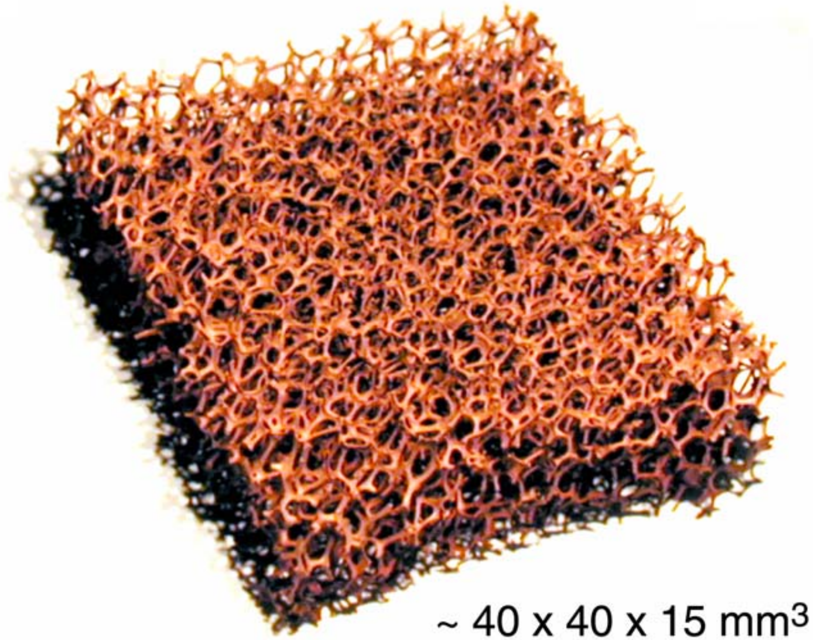
electron beam power – 4.2 kW

He gas flow – 7.5 slm

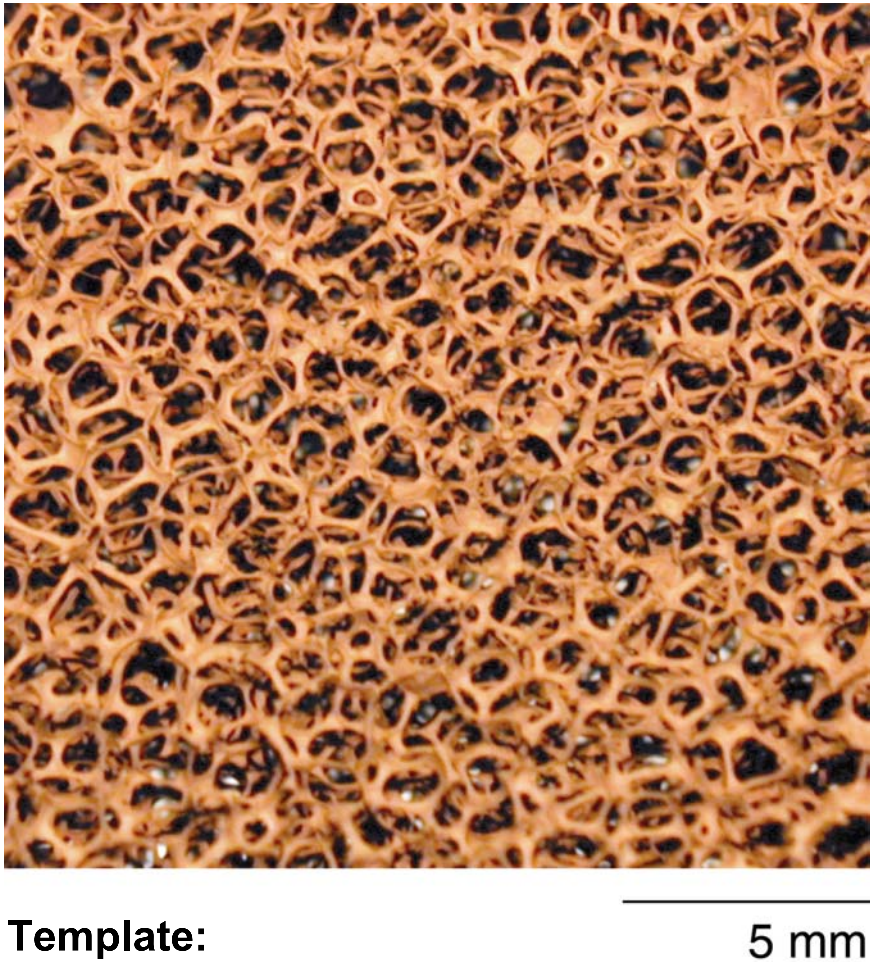
chamber pressure – 0.14 torr

nozzle pressure – 0.67 torr

pressure ratio – 4.8



~ 40 x 40 x 15 mm^3



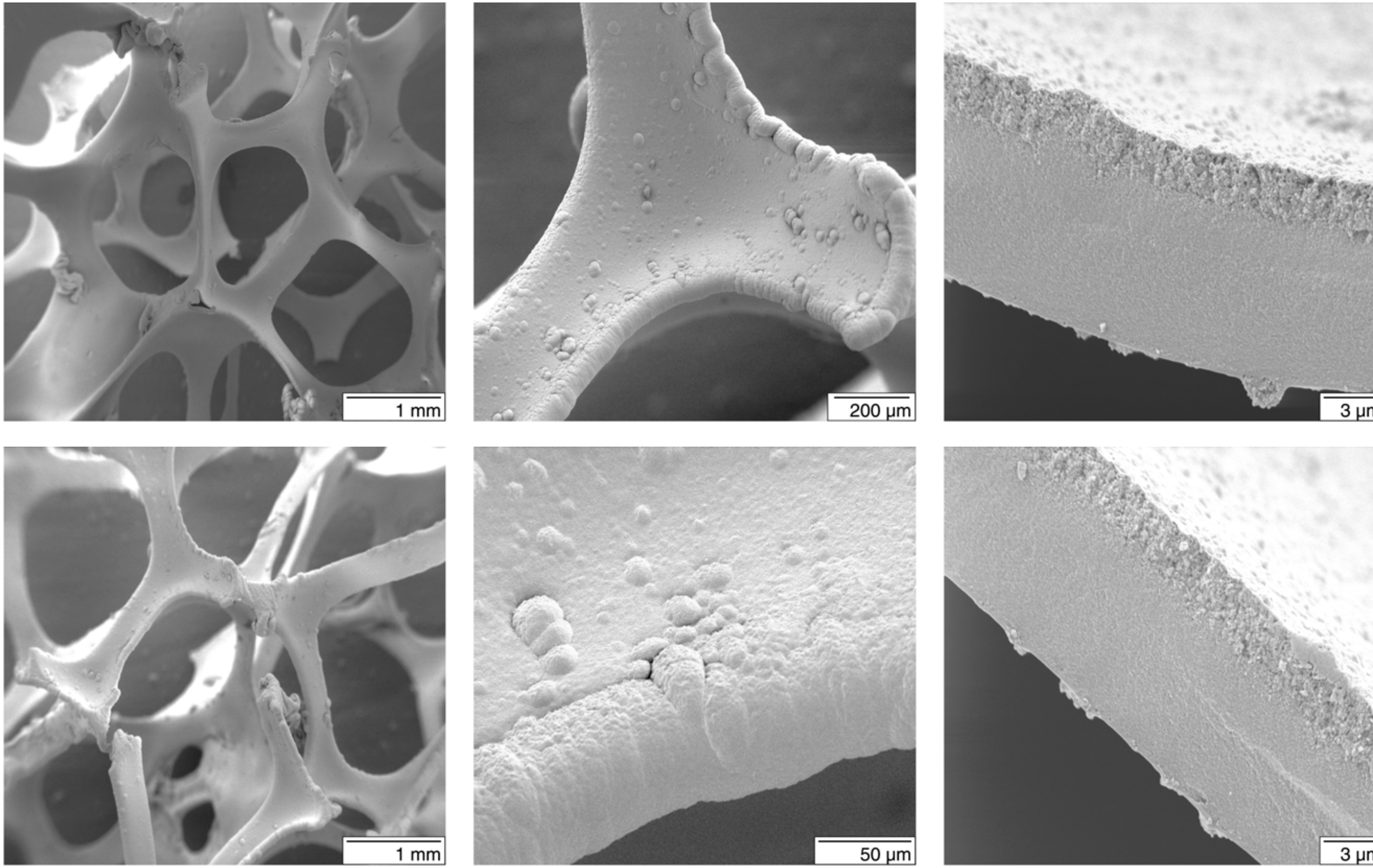
Template:

open cell, reticulated polyurethane foam

nominal pore size – 20 pores per inch

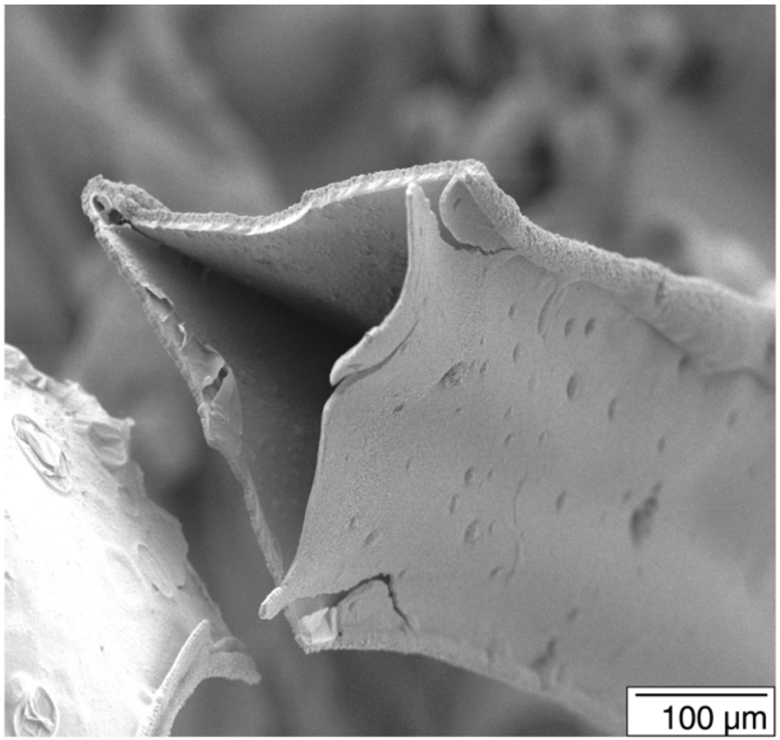
two- sided deposition (no rotation)

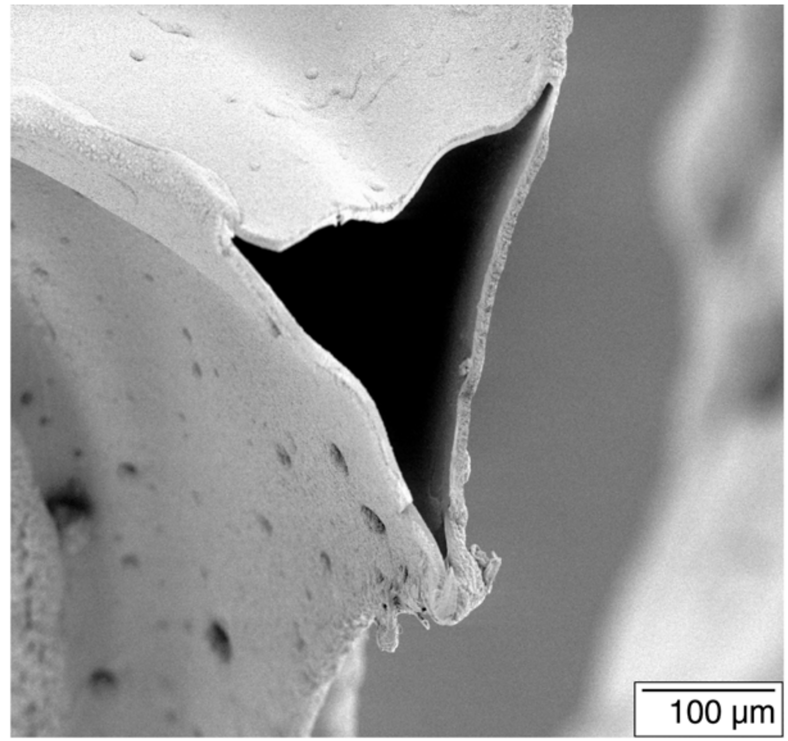
One Sided Deposition of Copper (front surface)



Polyurethane Foam: 20 pores per inch, 15 mm thick

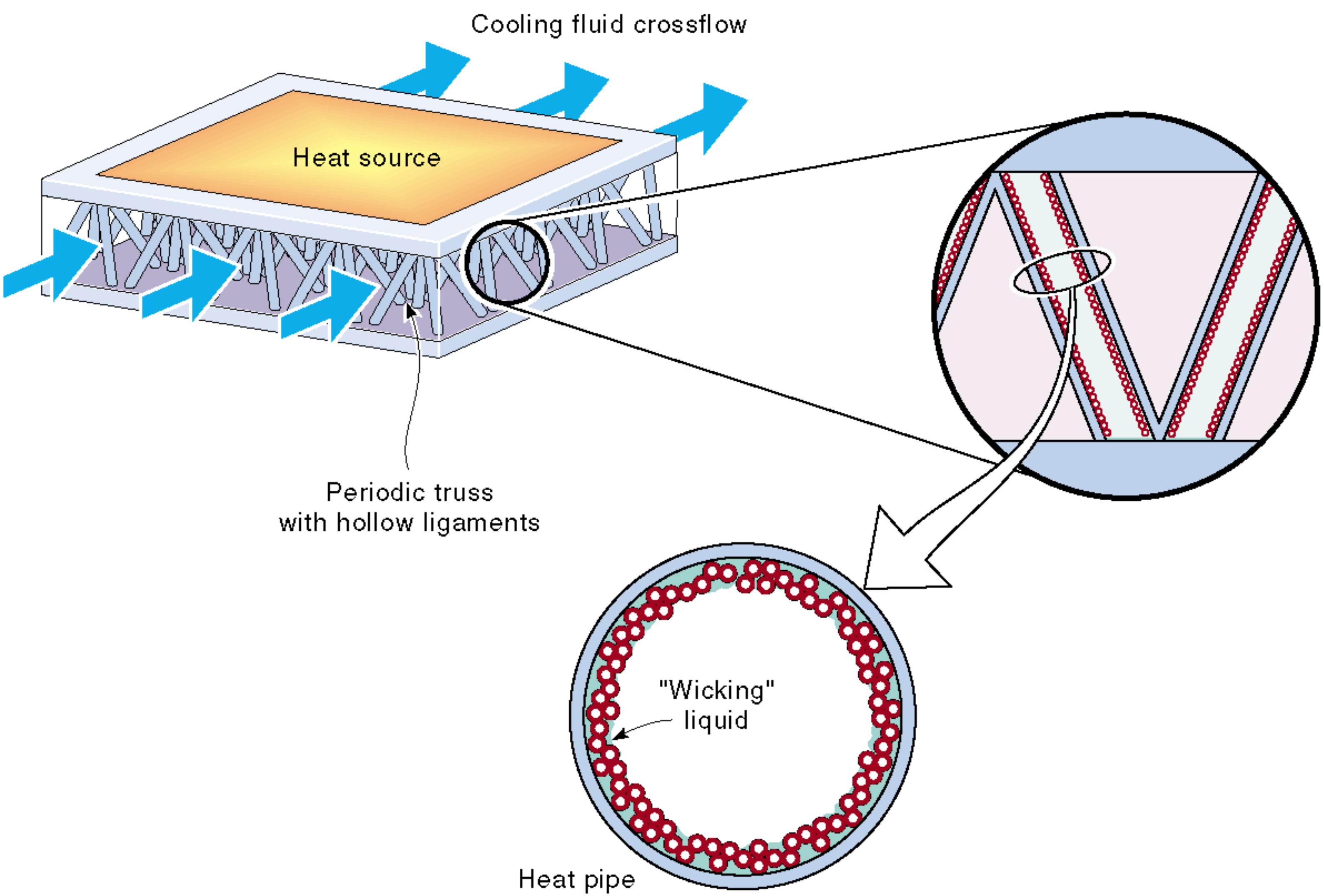
Uniform Coating - Copper Foam Ligaments





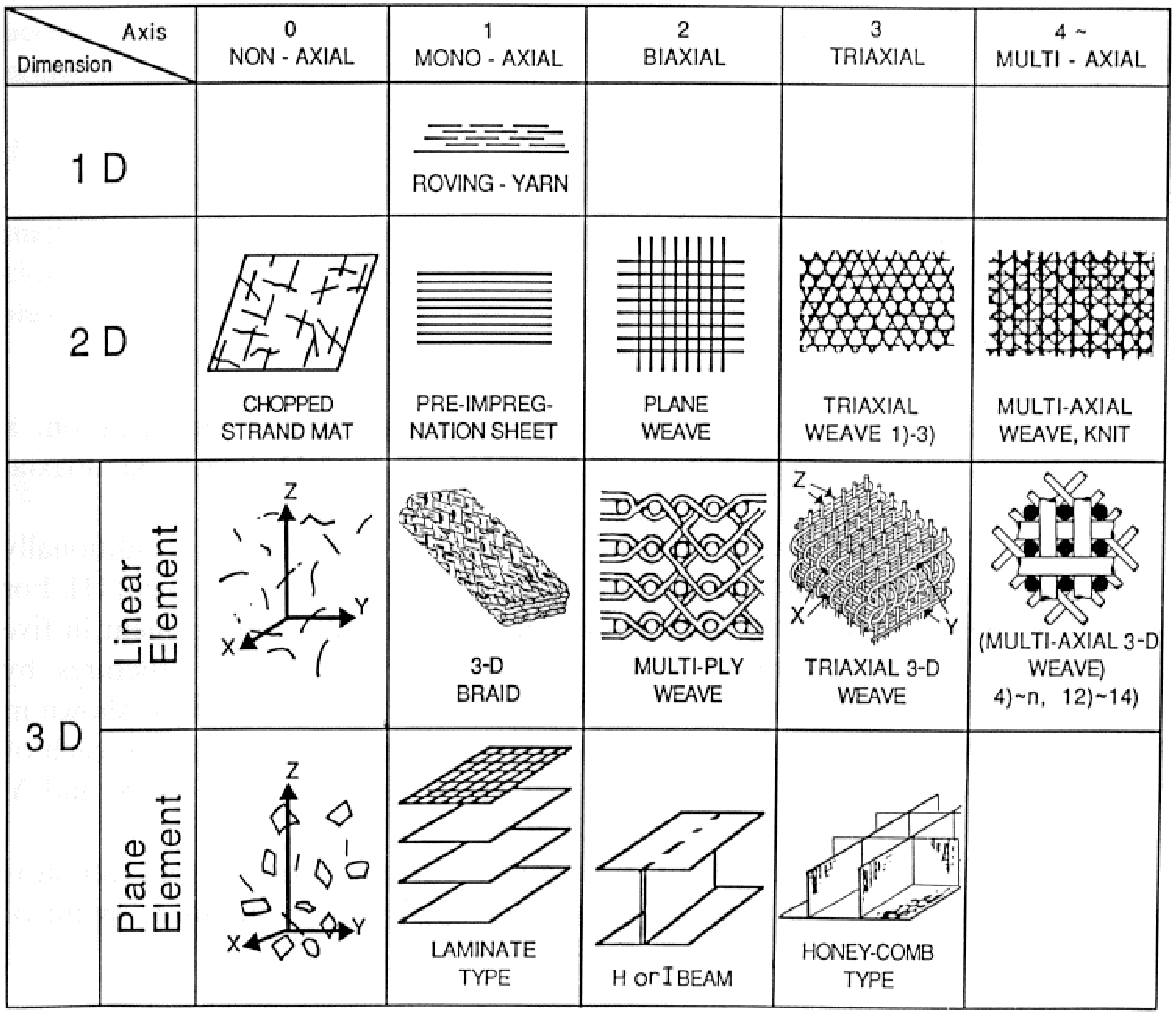
Polyurethane Foam: 20 pores per inch, 15 mm thick

Optimized Multifunctional Truss Structures?



Periodic Cellular Metal Heat Exchangers

Metal Textile Can Be Made In Many Forms



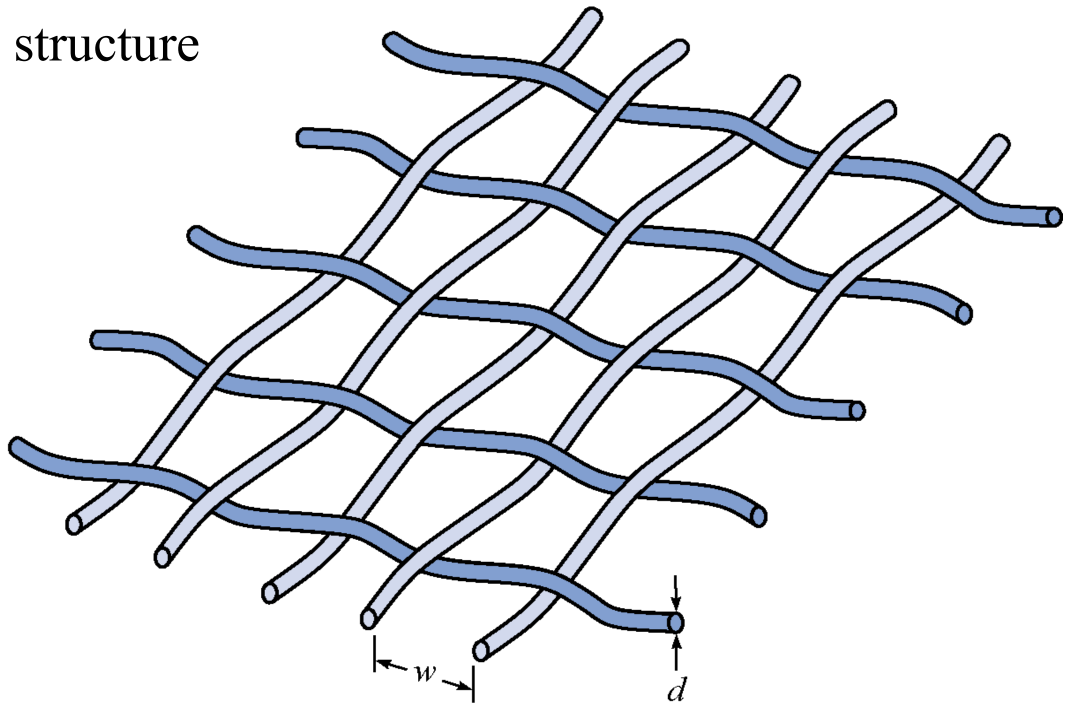
REFERENCE:

K. Fukuta, R. Onooka, E. Aoki and Y. Nagatsuka in S. Kawabata (Ed.), 15th Text. Res. Symp., The Textile Machinery Society of Japan, Osaka, 1984, pp. 36-38.

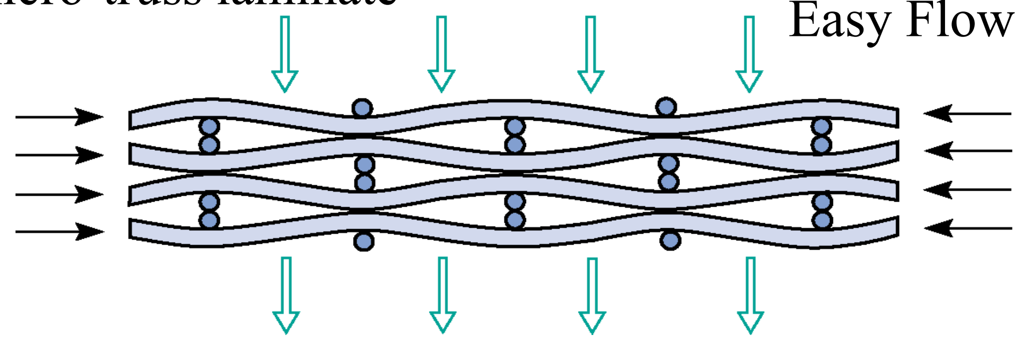
F.K. Ko, “Three Dimensional Fabrics for Composites”, In Textile Structural Composites, edited by T.-W. Chou and F.K. Ko, pp.129-171, Elsevier, 1989.

Lamination Construction

a) 2D woven metal structure

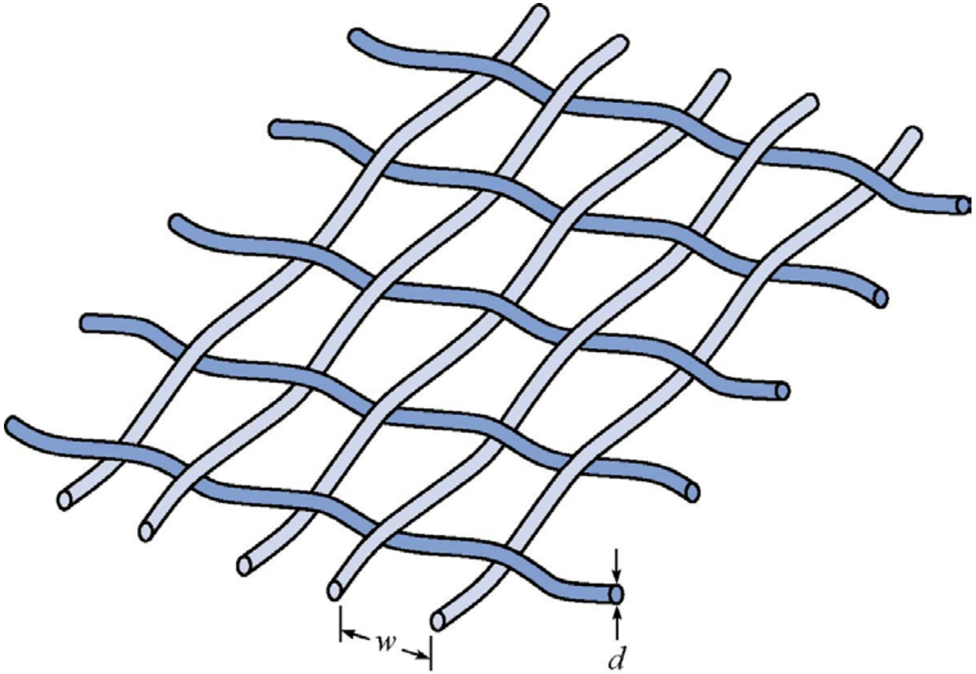


b) Woven metal micro-truss laminate



$\rho/\rho_s \approx \pi \mathbf{d}/4(\mathbf{w}+\mathbf{d})$ $\mathbf{E}/\mathbf{E}_s \approx \mathbf{0.5}\rho/\rho_s$ $\sigma_c/\sigma_{ys} \approx \mathbf{0.5}\rho/\rho_s$

Low Density Laminates

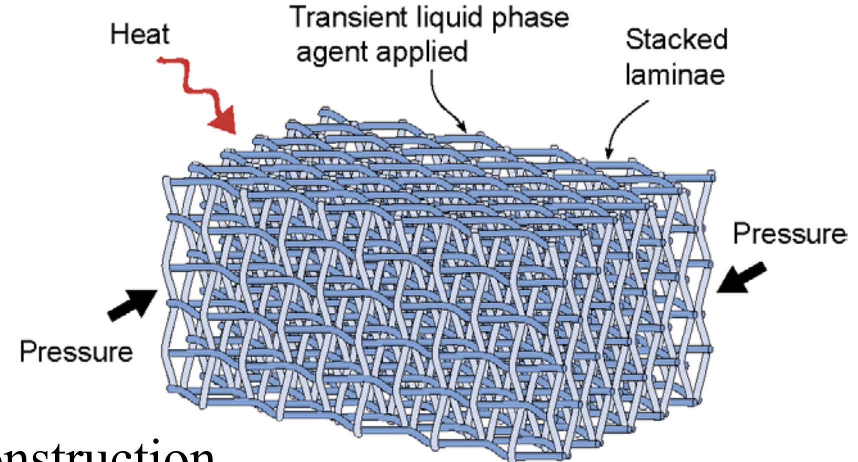


Plain Square Woven Metal Cloth

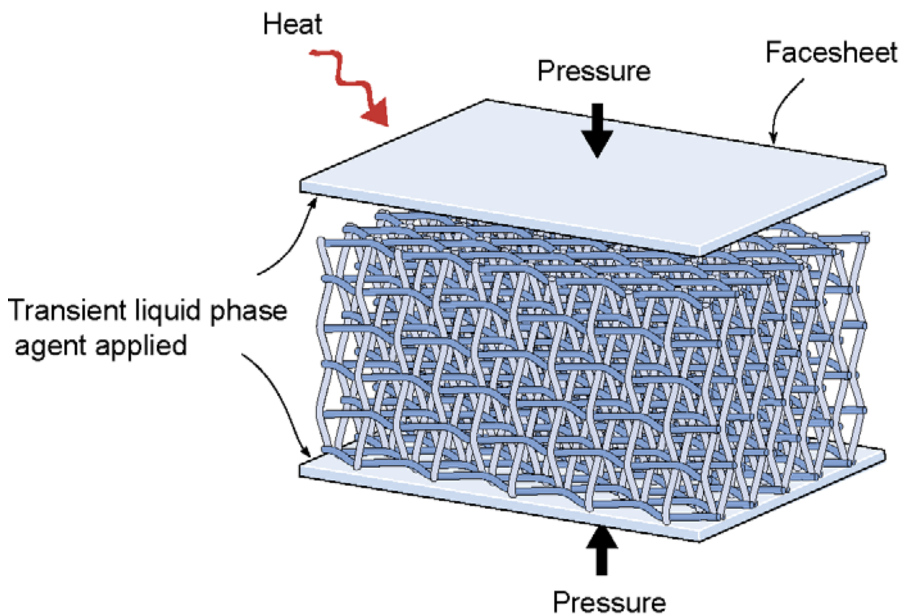
Designation	*d* (mm)	*w* (mm)	Relative density
1 (mesh/in)	2.03	23.4	0.06
10 (mesh/in)	0.635	1.91	0.20
100 (mesh/in)	0.114	0.140	0.35
Insect screening	0.229	1.18	0.13
High Transparency	0.0305	0.478	0.05

Bonding Method

- Micro-truss laminate core construction



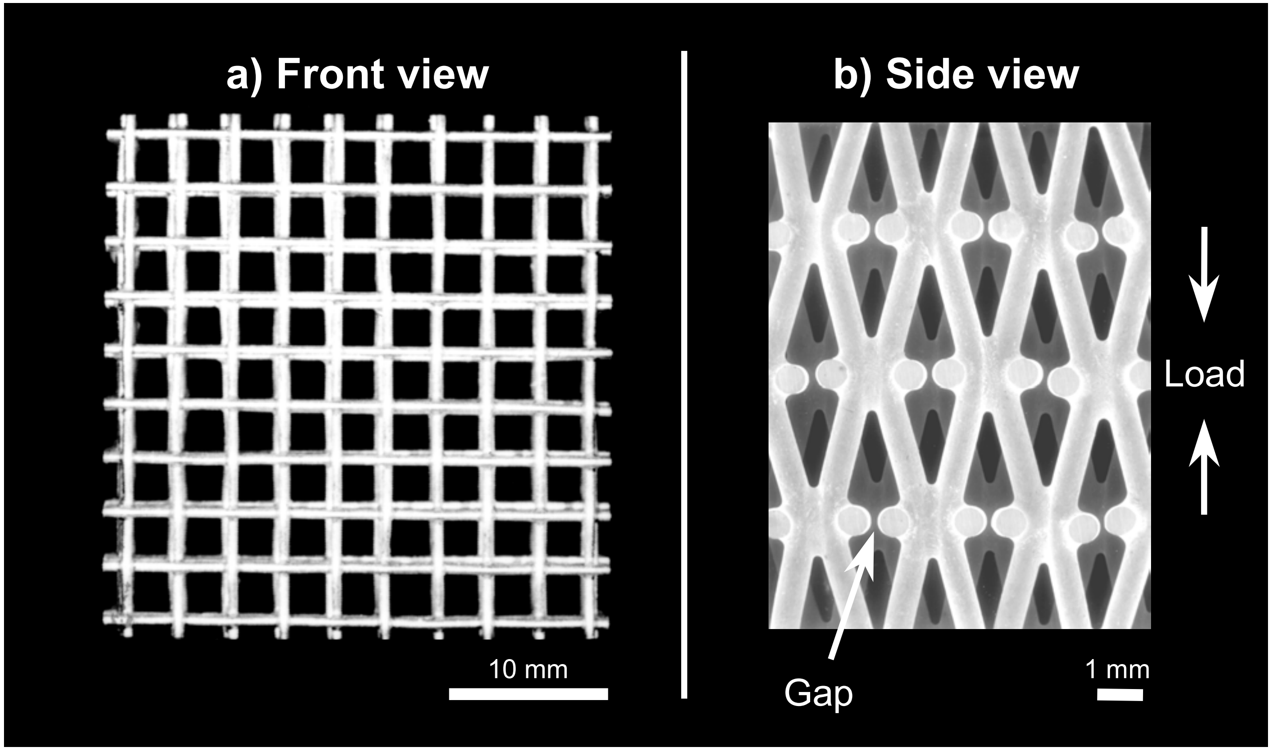
- Sandwich panel construction



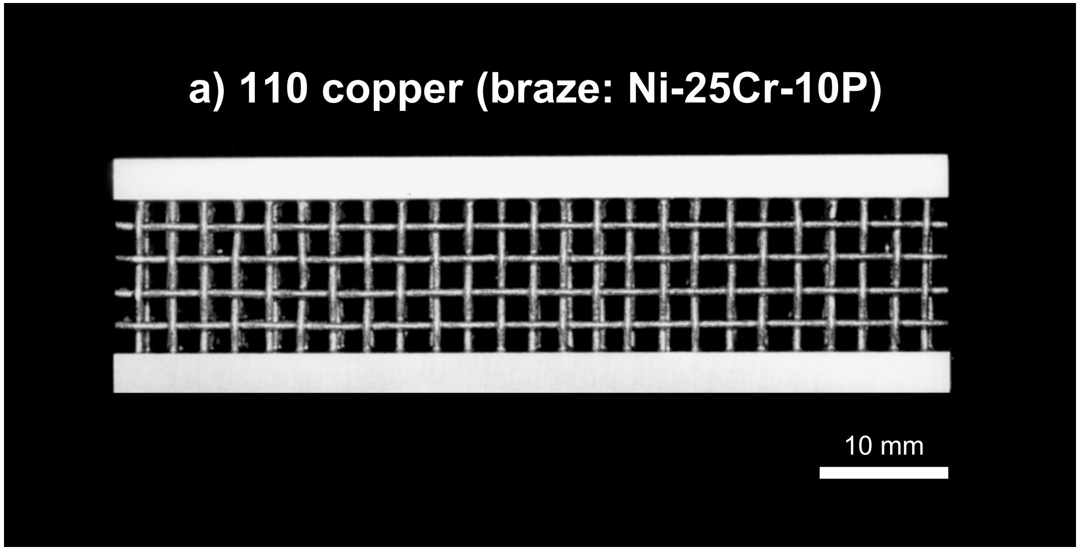
Multifunctional Micro-Truss Laminate (nichrome)

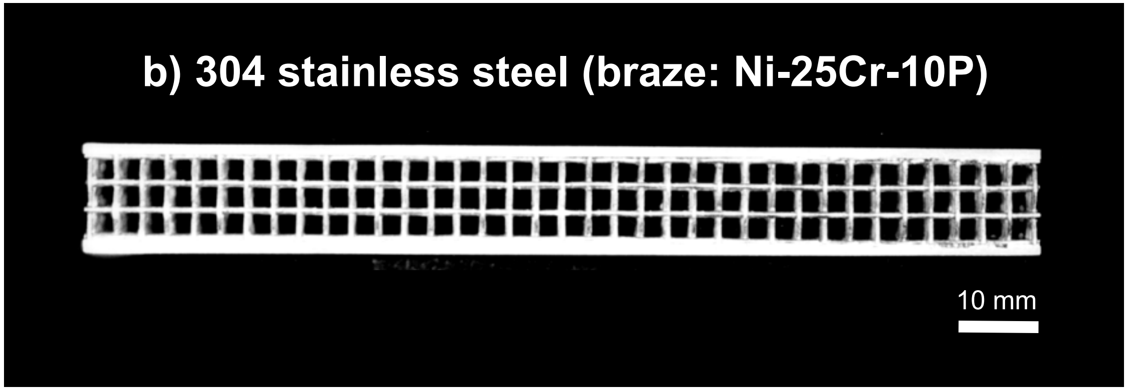
Easy Fluid Flow

Excellent Load Support

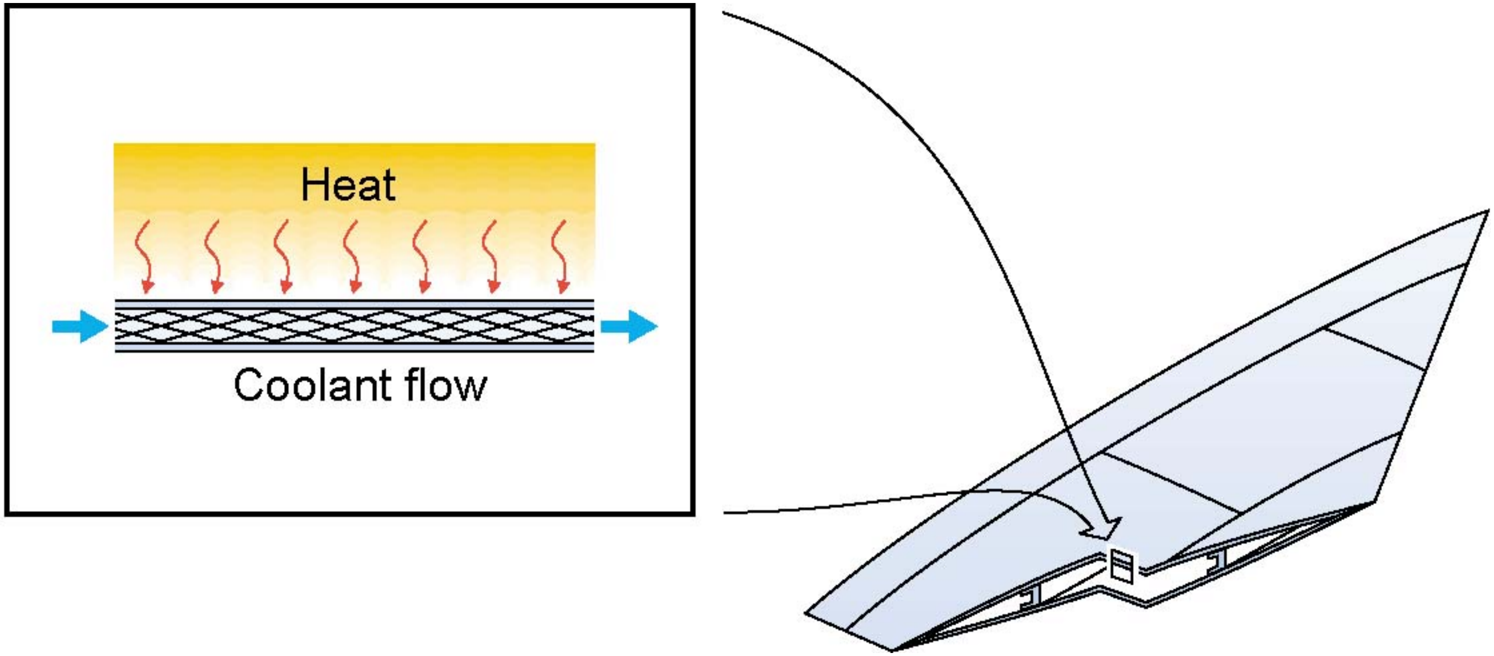


Materials Diversification





Actively Cooled Vehicle Skin Structures

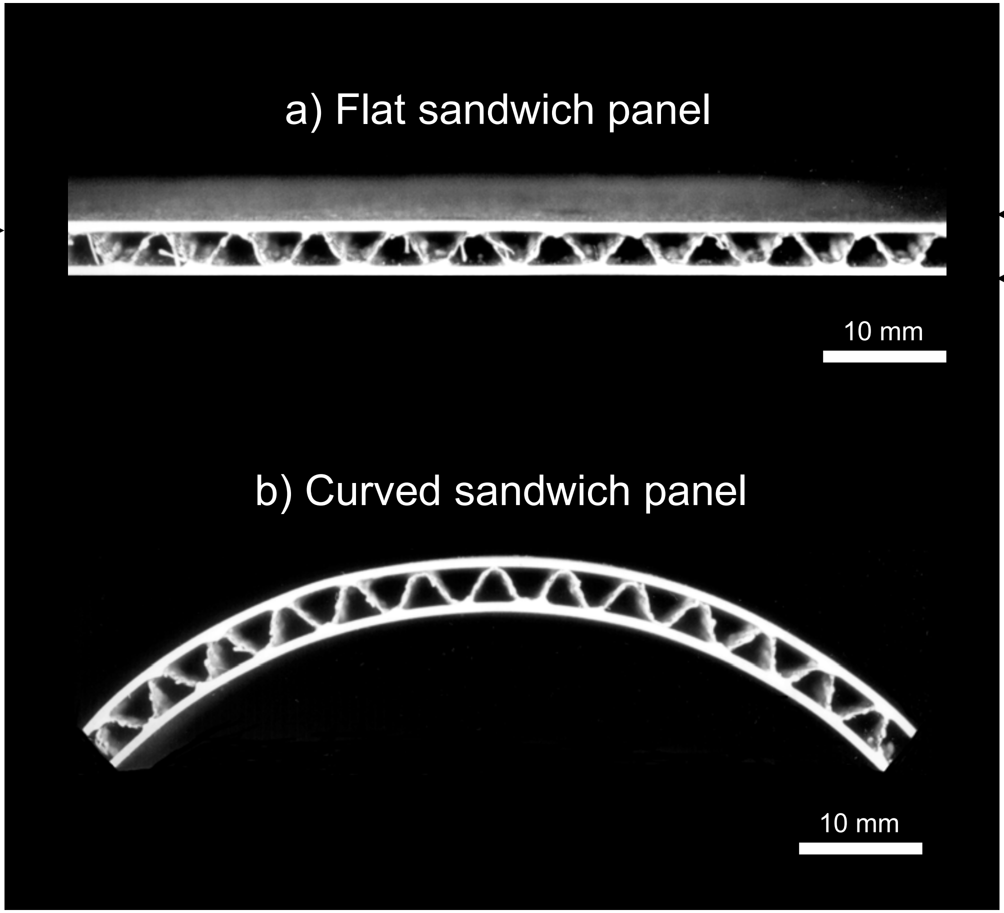


Possible solution: Open Cell Metal Core Sandwich Panel Wingskins

Sandwich Panel Structure Skin

Structurally efficient sandwich construction: two stiff, strong skins with a lightweight core, with a relative density in 3% range (to optimize mechanical response).

Corrugated metal textile core relative density: 0.04



Facesheet thickness: 0.61 mm

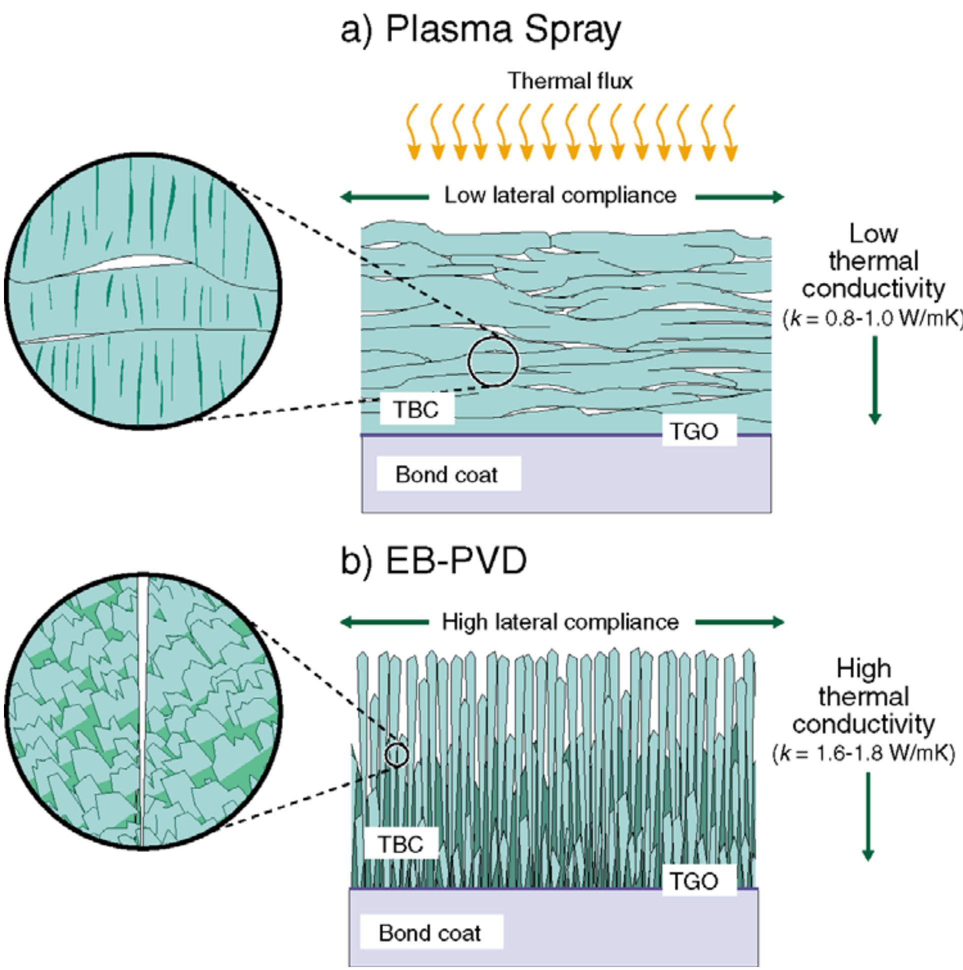
Advantages:

• High fluid permeability, complex shapes, many materials choices, utilize relatively inexpensive materials, (aluminum, titanium, nickel alloys). Low cost manufacturing**.**

THERMAL PROTECTION COATINGS

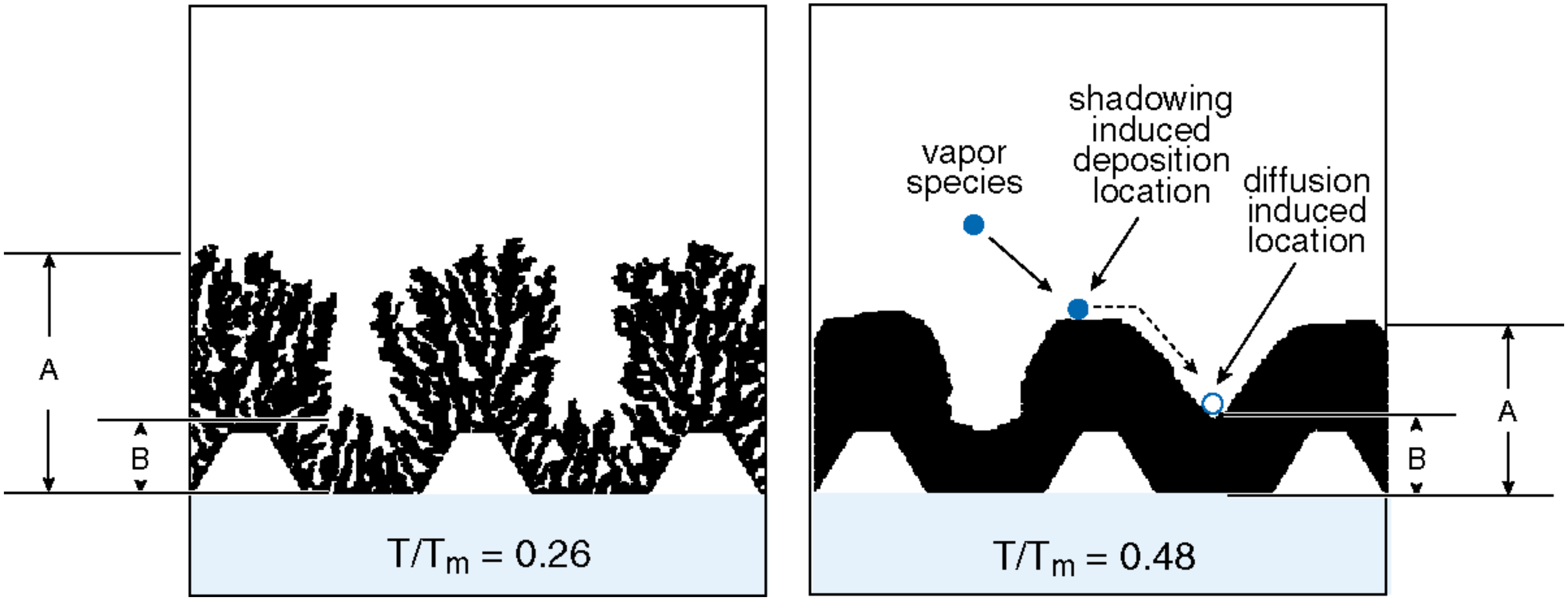
Pore Morphology Control for Low K Materials

Conventional Thermal Barrier Coatings



- **Pore volume fraction and morphology strongly effects both the thermal conductivity and thermomechanical performance of the TBC layer**
- **The deposition process establishes the initial pore fraction and morphology**
- **Sintering during service evolves the pore volume fraction, and morphology (and the thermal and thermo-mechanical properties).**
- **We are exploring concepts to <u>manipulate</u> porosity during deposition. Concepts extendable to other materials (lower thermal conductivity and sinter rates.**

Porosity Can Be Manipulated Via Flux Shadowing Mechanisms

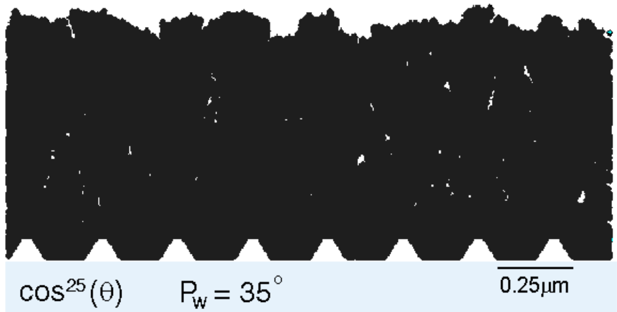


Flux angular distribution width = 120°, distribution peak = 0°

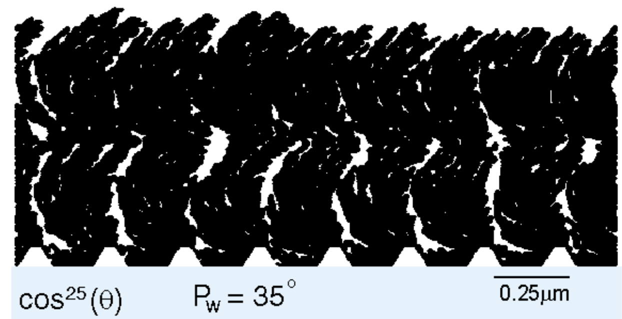
- **Increasing adatom surface mobility reduces flux shadowing by allowing an adatom to move to a shadowed region on the substrate**
- **Broadening the incidence angular distribution enhances the significance of shadowing and increases pore fraction.**

Pore Distribution in Vapor Deposited Coatings (Thermally Limit Surface Transport, Exploit Shadowing)

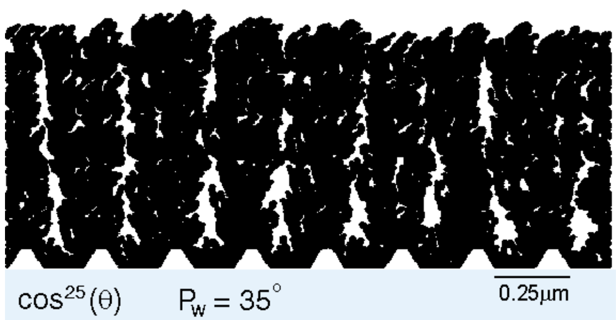
EB-PVD (no rotation)



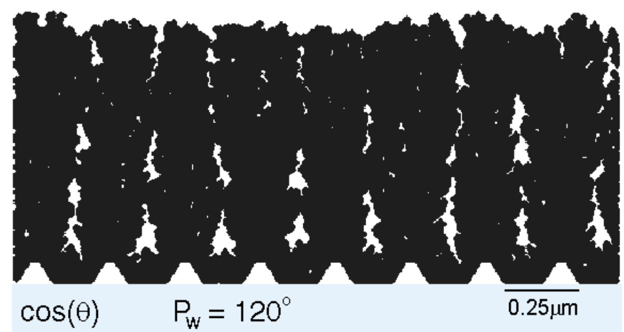
EB-PVD (rotation 250 mL/rev.)



EB-PVD (rotation 100 mL/rev.)

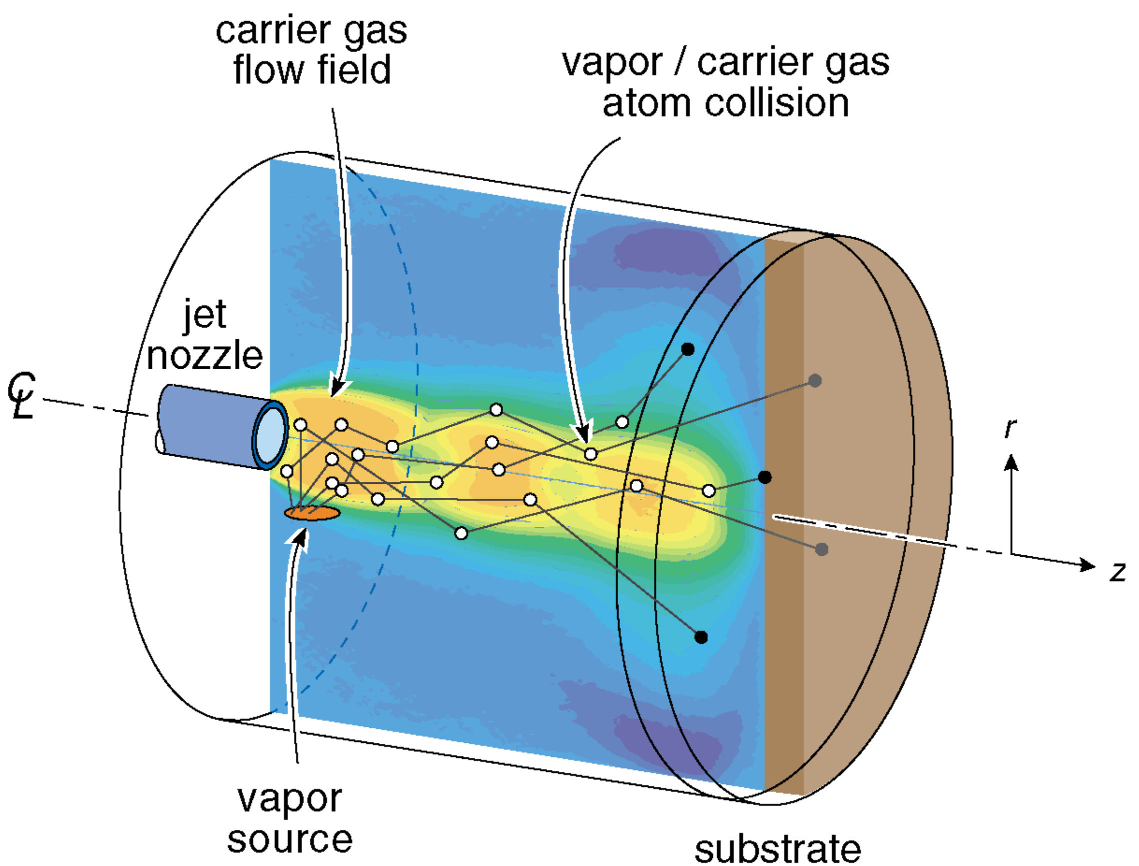


EB-DVD (no rotation)



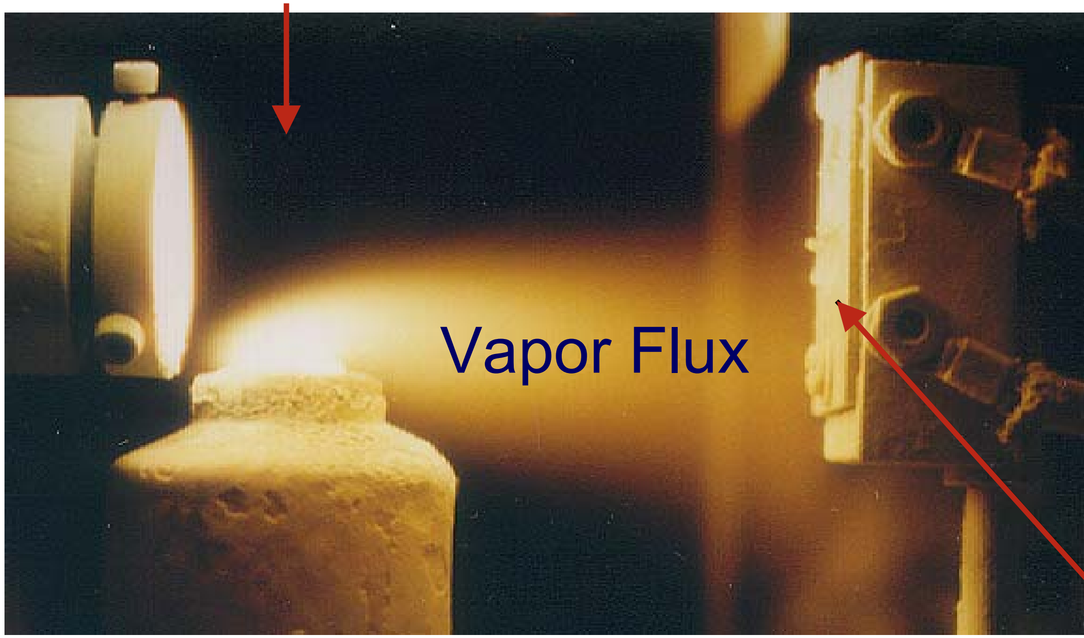
Substrate rotation is used in EB-PVD to broaden the effective incidence angle distribution and create thermo-mechanically beneficial intercolumnar pores.

EB-DVD I Concept

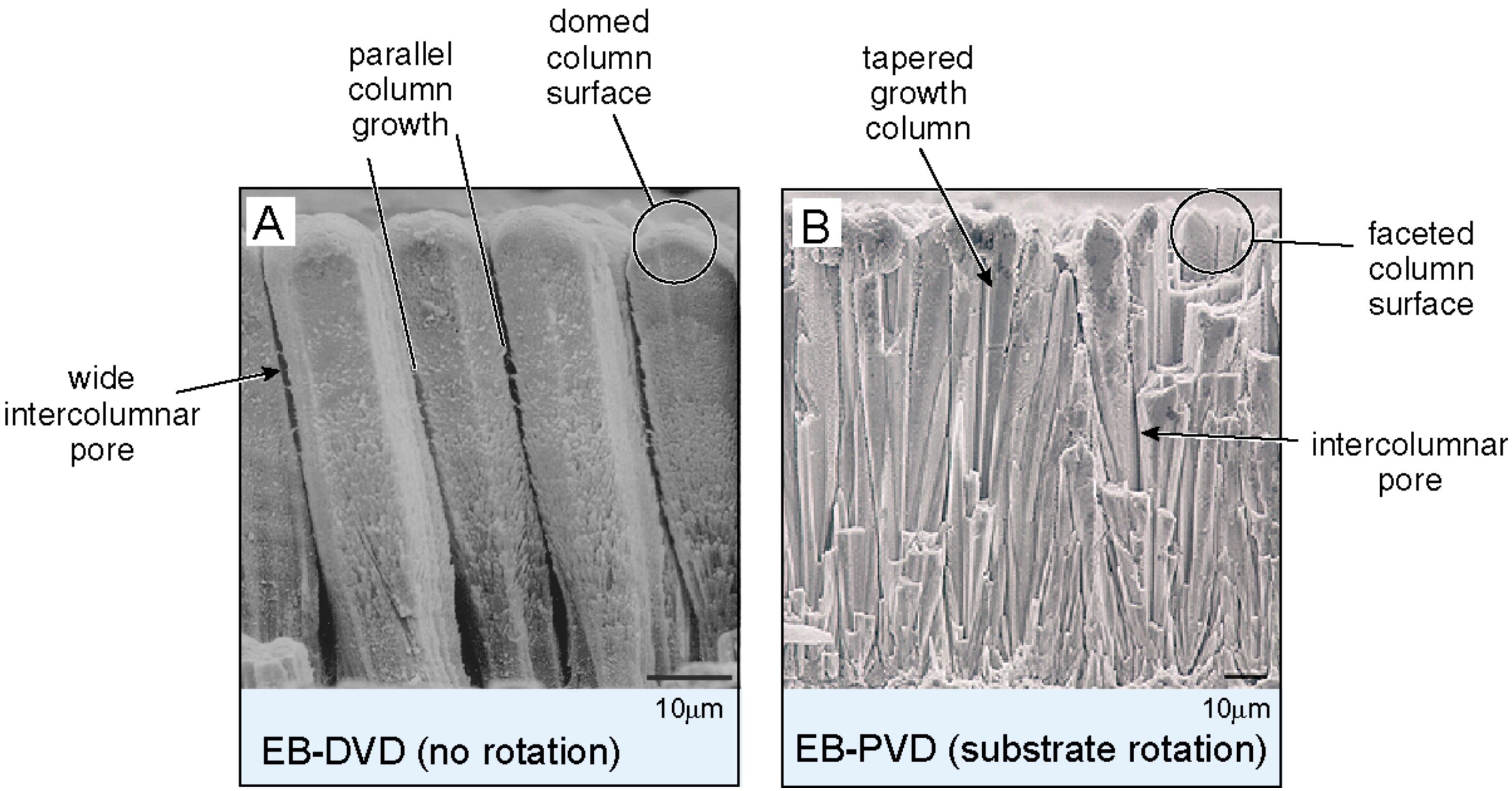


Gas phase scattering of vapor (by collisions with background gas) enables the incidence angle distribution to be broadened

EB-DVD Process Environment

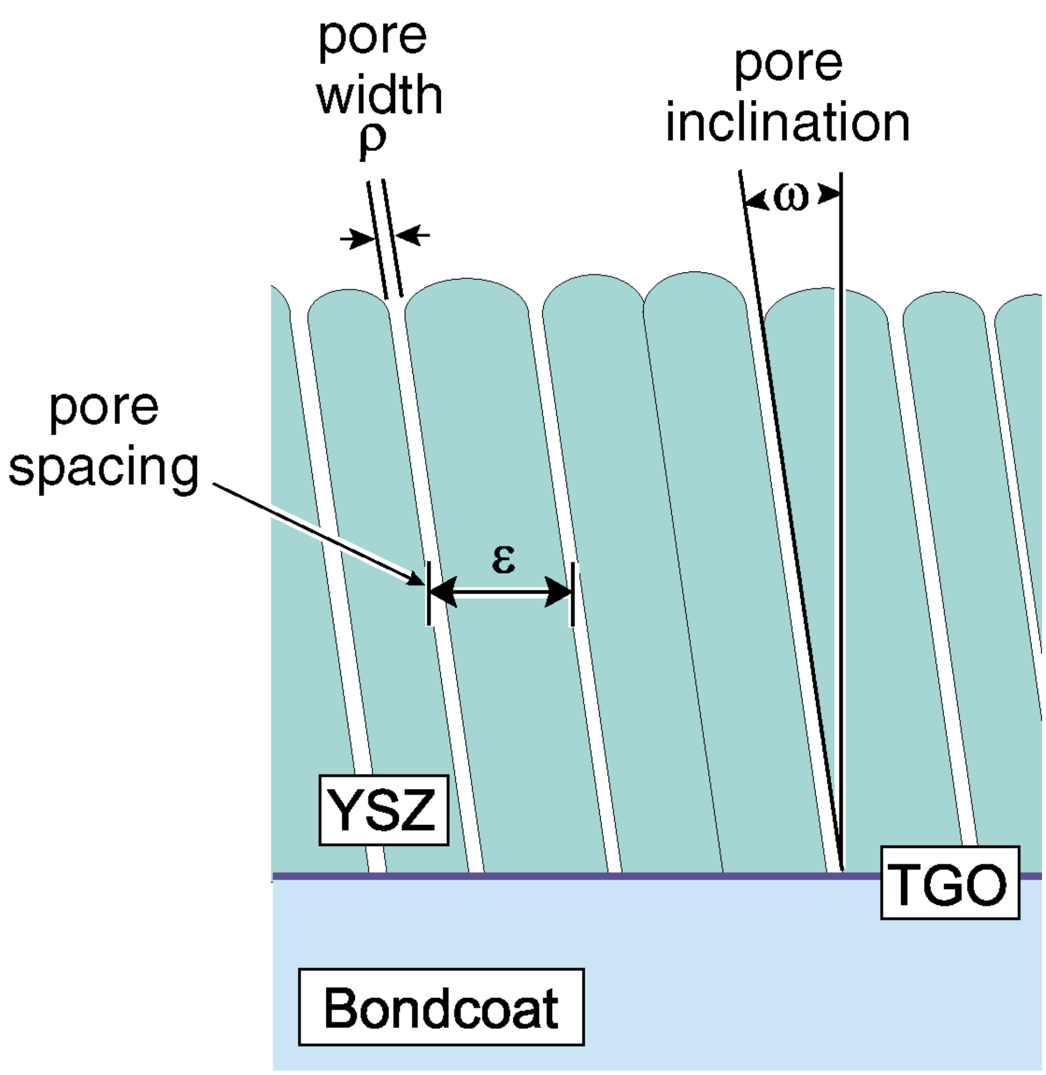


EB-DVD Versus EB-PVD

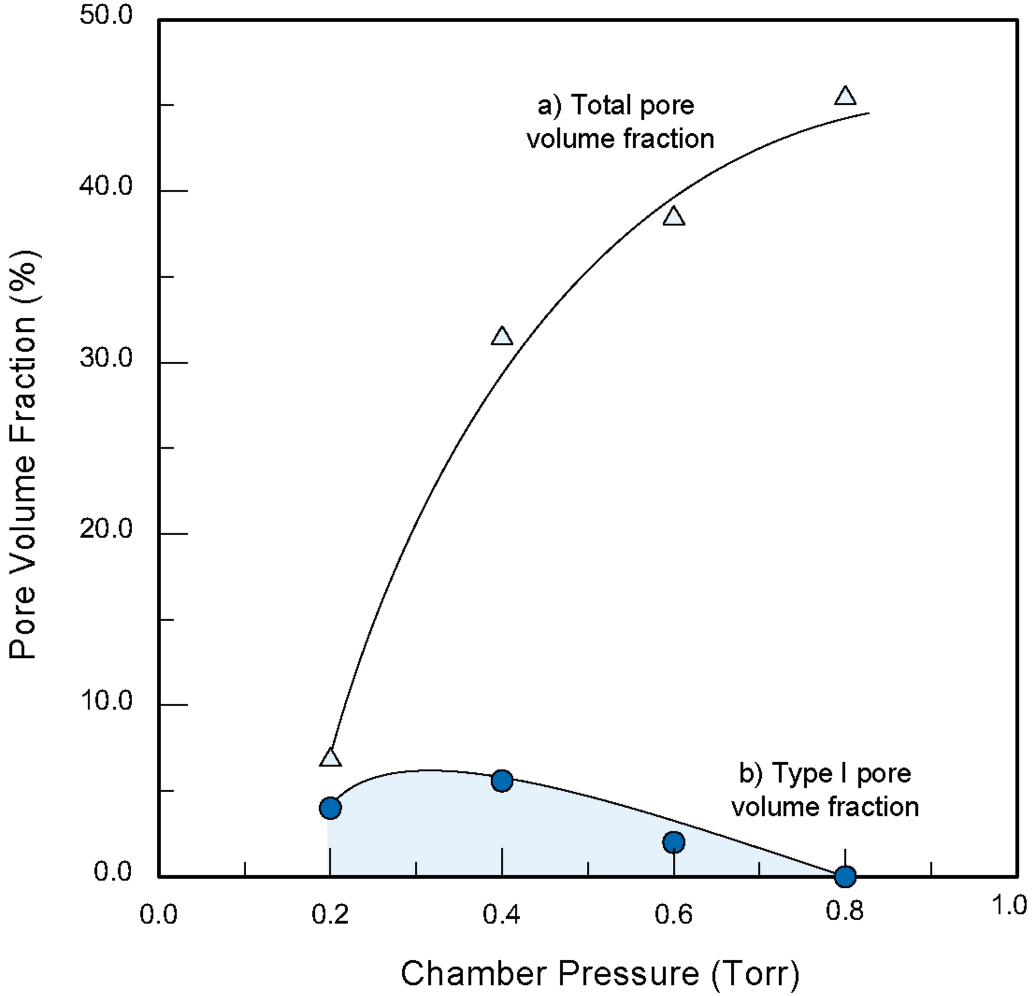


Coating Characterization

Type I Pore Parameters



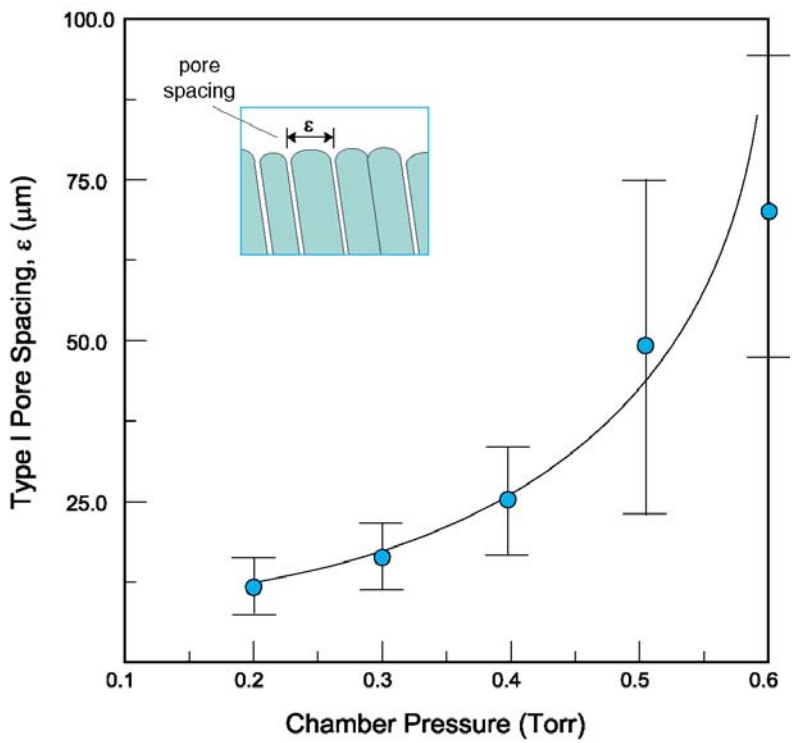
Coating Properties Constant Upstream Pressure (P_u=2Torr)



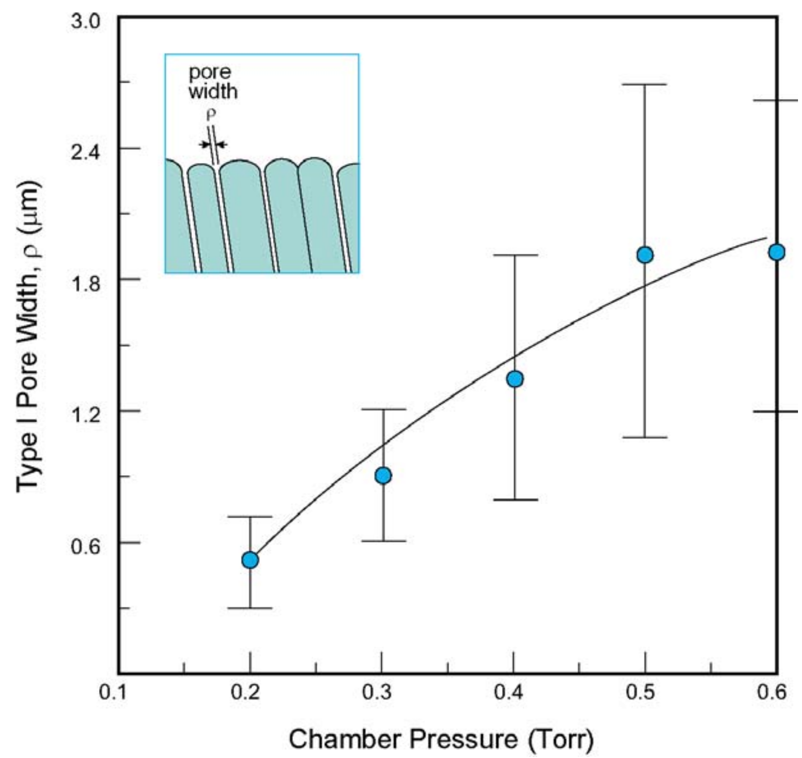
- Total pore volume fraction greatly increase with chamber pressure
- High evaporation rates and low pressure ratios also promoted a high pore volume

Morphology at Constant Upstream Pressure

Type I Pore Spacing



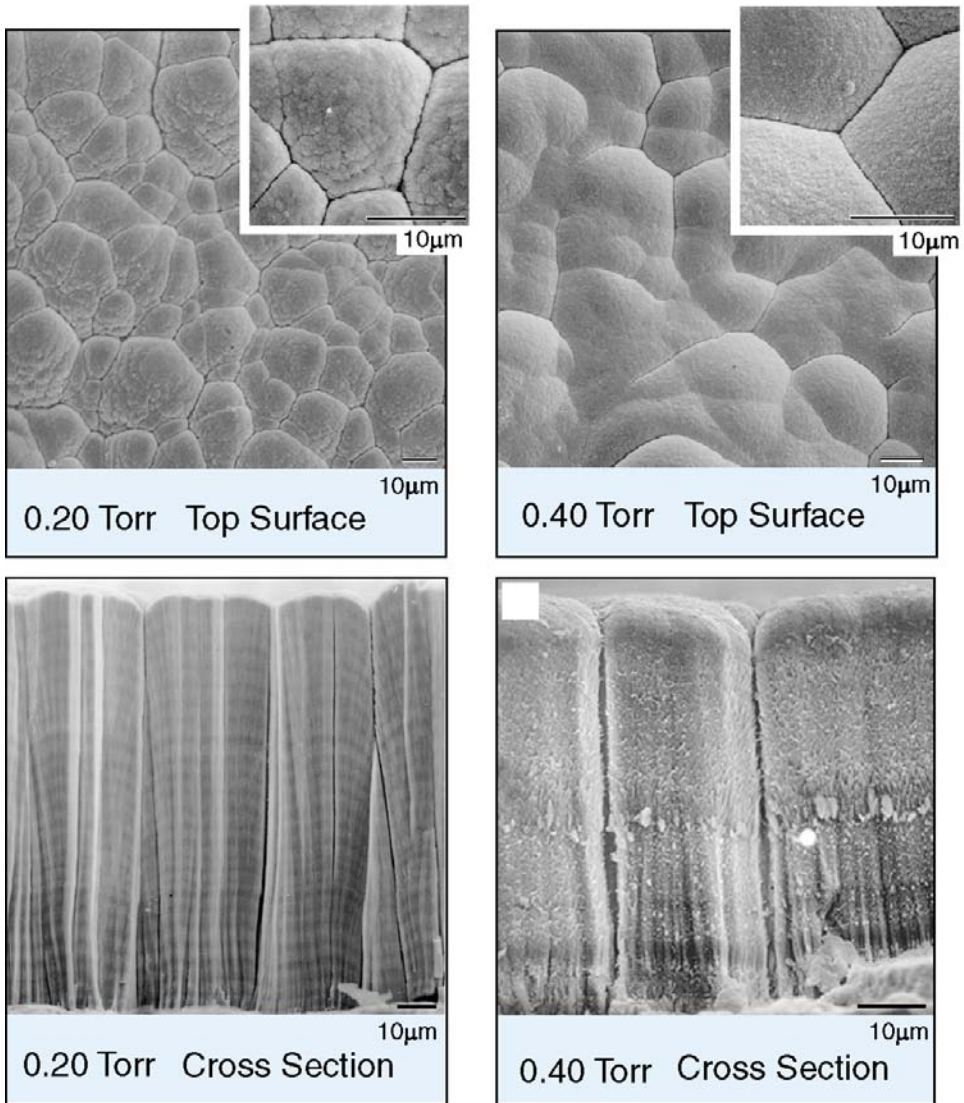
Type I Pore Width



•**Type I pore spacing and width increase with chamber pressure**

Thermal Conductivity (Constant Upstream Pressure)

Rate = 5.0 μm/min. Flow = 8.0 slm He Temp. = 1000^{o}C

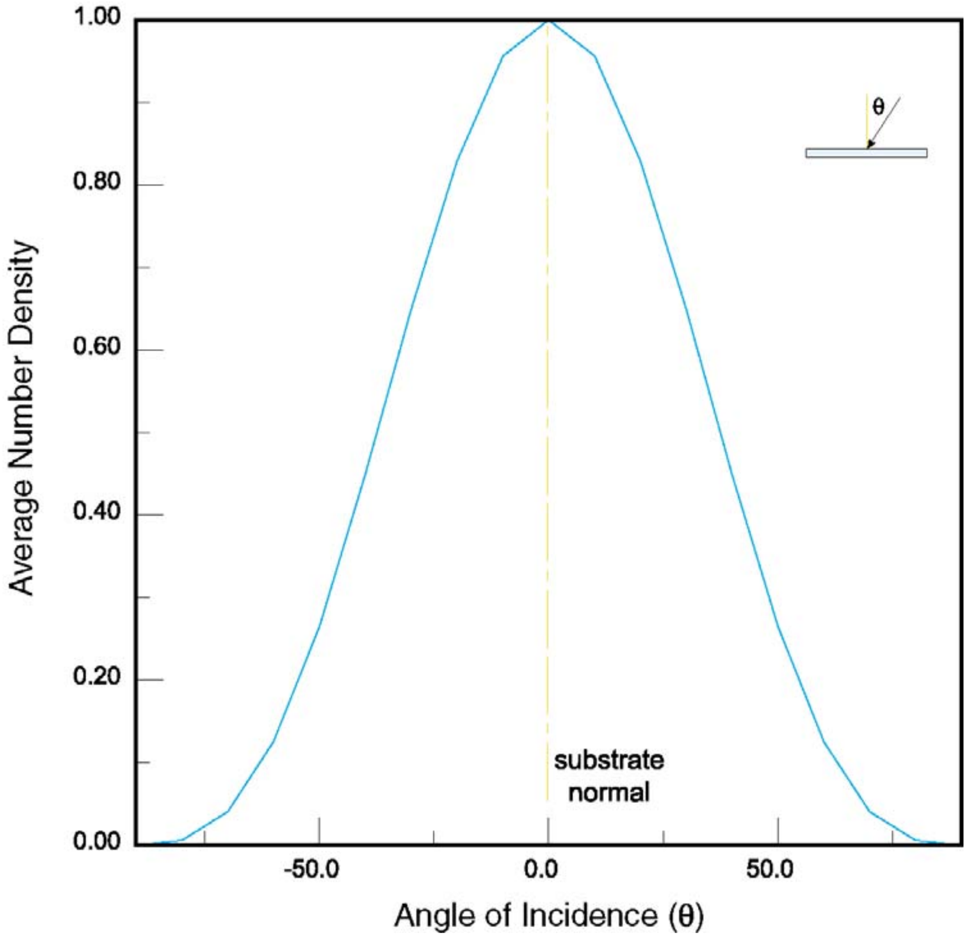


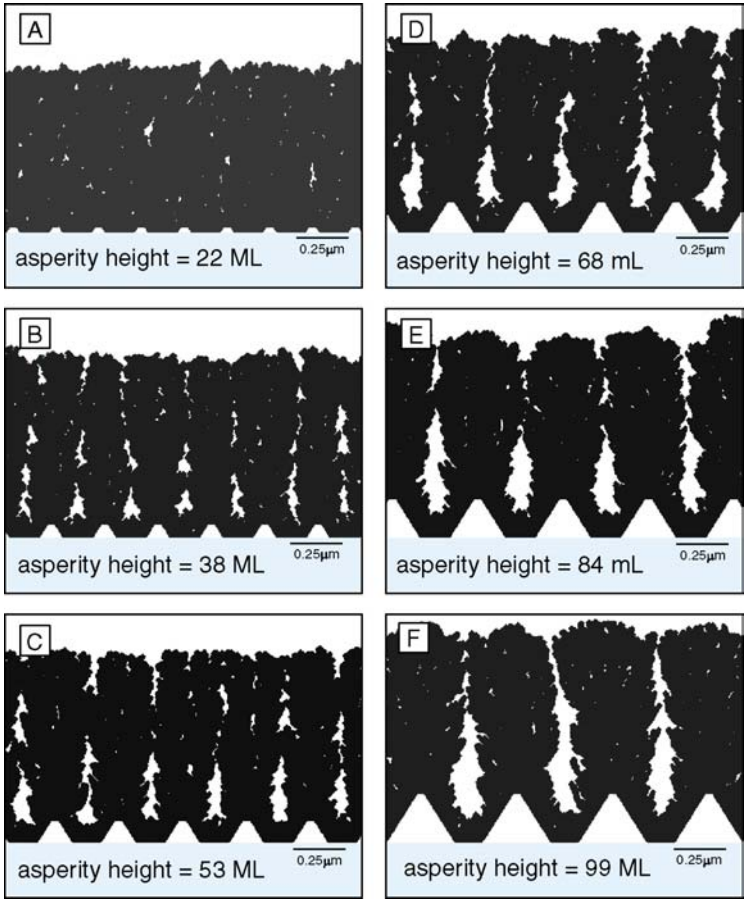
κ = 1.9 W/mK
ρ = 5.3 g/cm^3

κ = 1.3 W/mK
ρ = 3.9 g/cm^3

kMC Simulations

Asperity Height



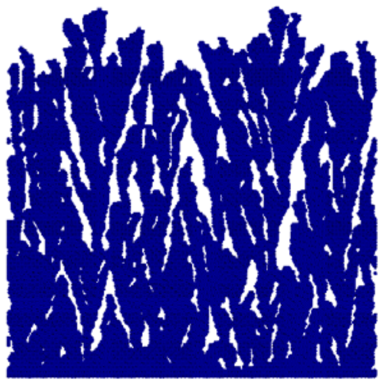


Large asperities promote Type I pore formation

Pore Morphologies

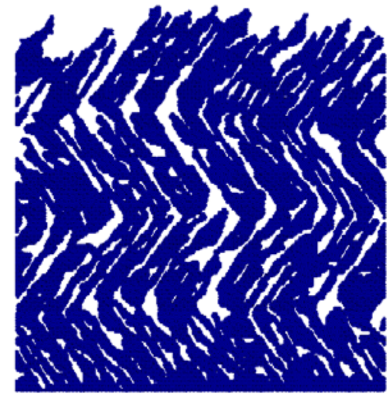
"Motion and Dwell" Substrate Manipulation (+/- 45°)

T/T_m= 0.22, Rate = 3.0 μm/min., 32000 nickel atoms

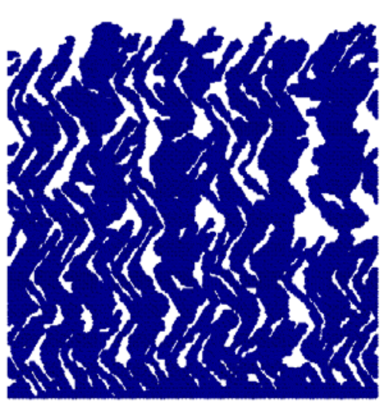


stationary substrate
(density = 0.74)

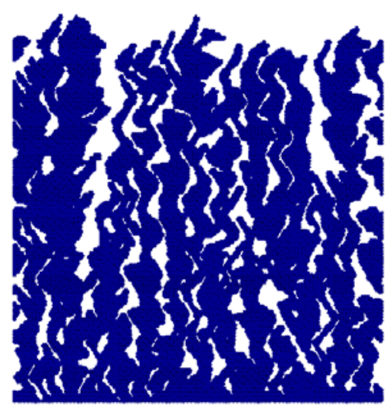
inclined substrate (45°)
(density = 0.67)



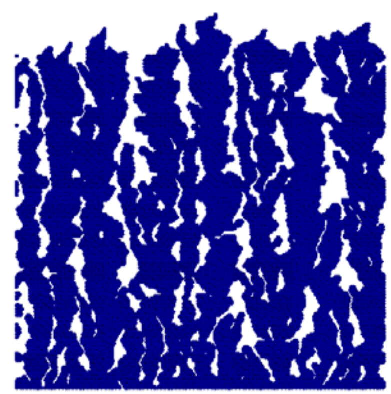
40mL dwell
(density = 0.69)



20mL dwell
(density = 0.70)

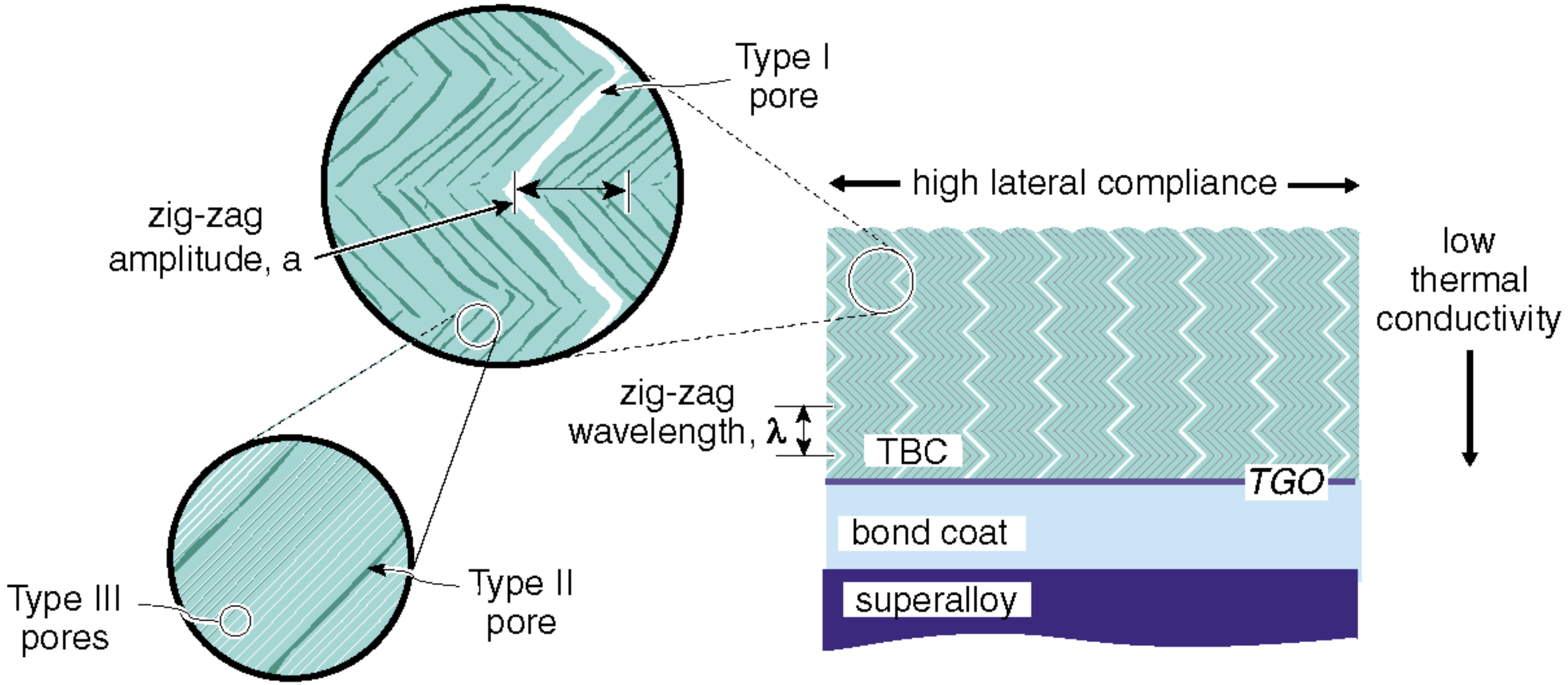


10mL dwell
(density = 0.71)



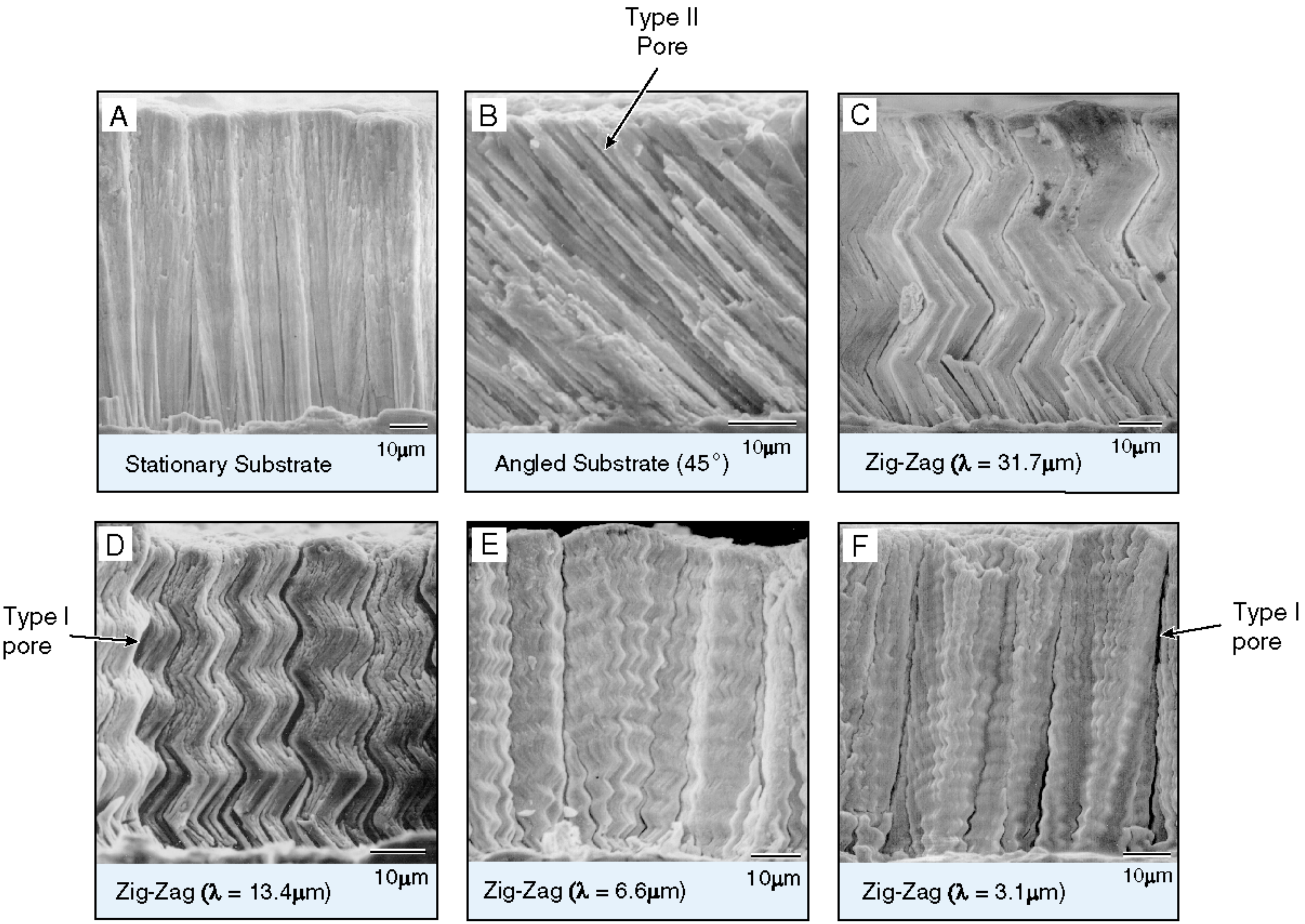
5mL dwell
(density = 0.73)

Zig Zag TBC Coating Concept

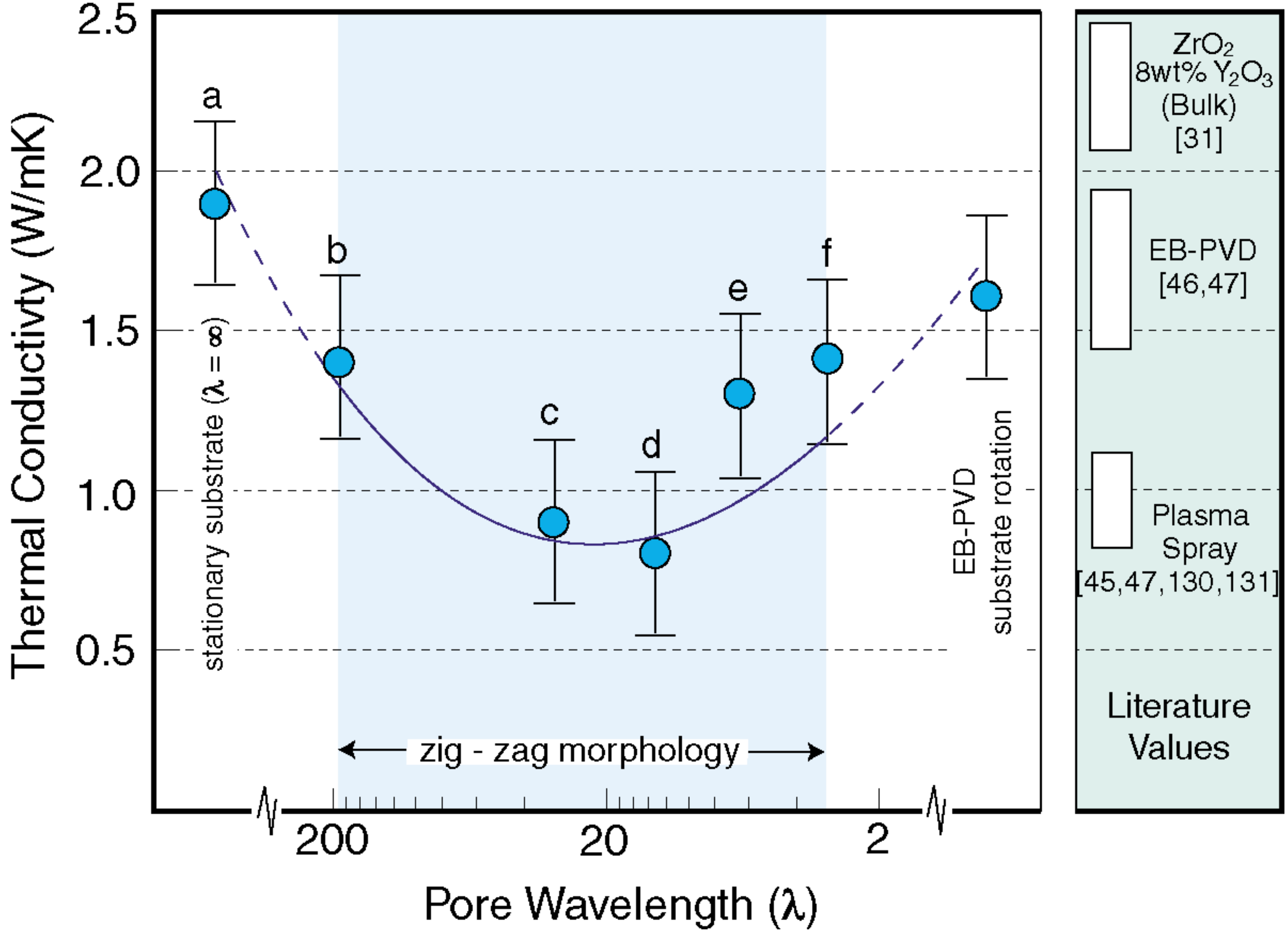


Pore morphology optimized for low thermal conductivity and high thermomechanical resistance

TBC Microstructure



Thermal Conductivity Measurements



***Type I pore nucleation control**

Summary

- Emerging manufacturing concepts (rapid prototyping), directed vapor deposition and 3D weaving are creating new opportunities for meso structure control.
- These manufacturing approaches facilitate novel thermal engineering concepts:

  -Microheat pipe structures for 3D heat exchangers

  -Low backpressure multifunctional heat exchangers

  -Ultralow conductivity thermal protection systems that utilize pore morphology control